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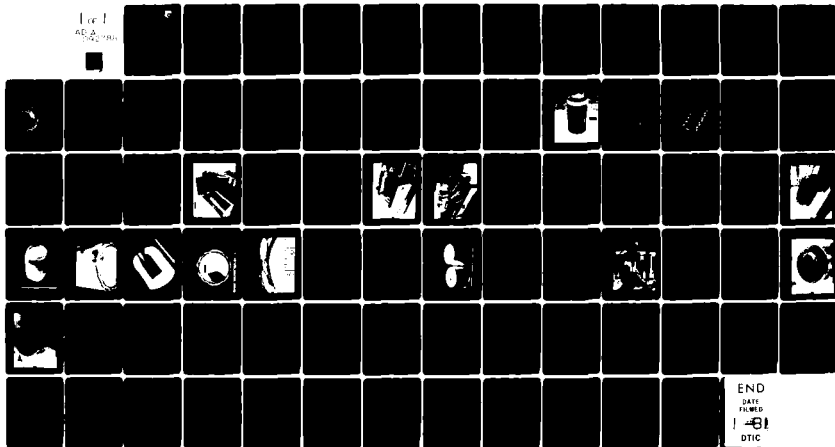
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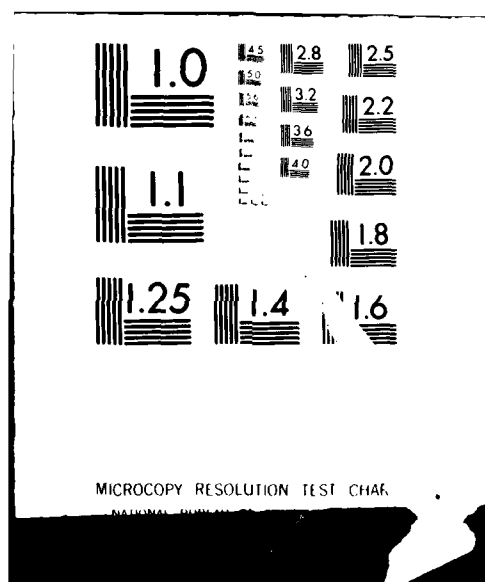
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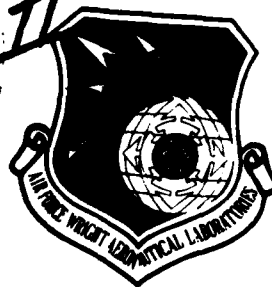




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SUPERPLASTIC FORMED AND DIFFUSION BONDED TITANIUM LANDING
GEAR COMPONENT FEASIBILITY STUDY

Rockwell International
North American Aircraft Division
P. O. Box 92098
Los Angeles, California 90009

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July 1980

Technical Report AFWAL-TR-80-3081
Final Report for Period March 1979 - July 1980

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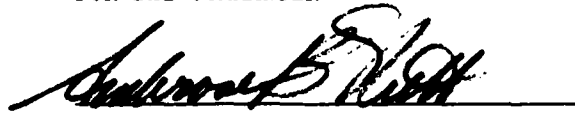
This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.


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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the development, fabrication and testing of a section of a main landing gear outer cylinder. The program demonstrated the feasibility of using the SuperPlastic Forming with concurrent Diffusion Bonding (SPF/DB) fabrication process to build a titanium cylindrical sandwich structure with a weight savings of 8-1/2 percent over the baseline steel cylinder. The development of joints, stop-off application and tooling is described. Structural analysis and subsequent structural testing proved			

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20. that the cylindrical sandwich design is capable of meeting the loads that the outer cylinder of the landing gear would be subjected to in a current first line fighter aircraft.

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PREFACE

This final report represents the results of the Superplastic Formed Diffusion Bonded Titanium Landing Gear Feasibility program accomplished by North American Aircraft Division (NAAD) of Rockwell International Corporation, on Contract F33615-79-C-3401, for the Flight Dynamics Laboratory of the Air Force Wright Aeronautical Laboratories. The work was accomplished under Air Force Program Element 62201F, Project 2402, Task 240201, Work Unit 24020110. It is published for information only and does not necessarily represent recommendations, conclusions, or approval of the Air Force.

This work was performed by the Advanced Metallic Group and the Material and Processes Laboratory, of NAAD. The Air Force Project Engineers for this effort were Mr James R. Hampton, Mr Wallace C. Buzzard, and Mr George J. Sperry of AFWAL/FIEM.

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The program was initiated on 19 March 1979 and completed on 07 July 1980.

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SECTION I

INTRODUCTION AND SUMMARY

1. BACKGROUND

The increasing cost and weight of aircraft systems procured by the Air Force has become a major concern of the U. S. Government. As a result, military planners are taking positive steps to reverse this trend. One of the leading candidates for cost and weight reduction is aircraft landing gears, which historically account for around 12 percent of the structural weight and 4 percent of the cost of the airframe. In addition, these components experience high operational costs and life cycle costs because of premature failure due to fatigue and stress corrosion cracking.

The Air Force, recognizing that it is imperative that these problems be addressed, has funded through AFWAL/FIEM a number of studies to improve landing gear systems. Among the most recent of these is a study (Contract F33615-76-C-3021) by Rockwell which compared advanced composites, metal matrix composites, and advanced metallic (SPF/DB titanium) designs to the baseline steel design. This study showed a 33 percent reduction in life cycle costs could be attained by using SPF/DB titanium in lieu of conventional MLG materials, see figure 1.

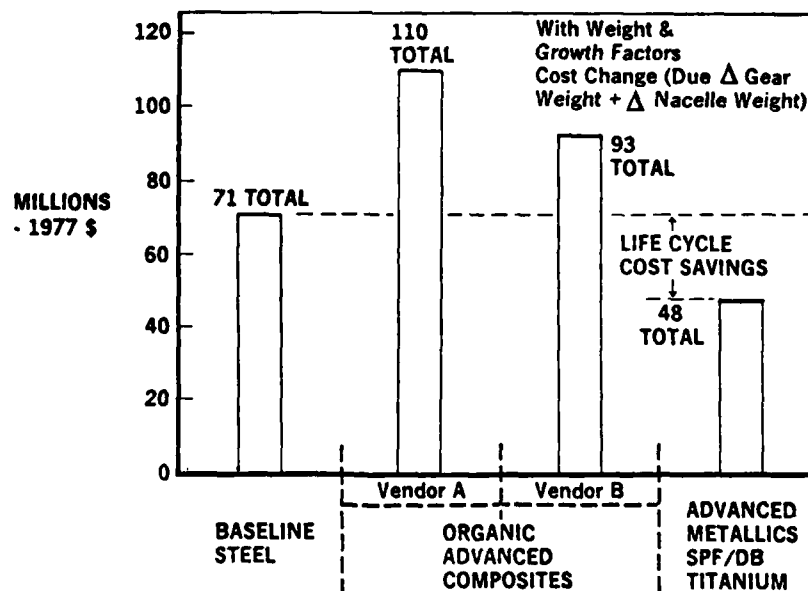


Figure 1. Life Cycle Comparison Chart (Millions of 1977 Dollars)/Landing Gear System - ATS Airplane

Titanium has recognized advantages in strength, efficiency, corrosion resistance, and elevated-temperature properties. These advantages have formerly been offset by the limitations and high costs of conventional fabrication. However, titanium fabrication technology is a new area where significant gains have been made in elevating the competitive rank of titanium in the list of candidate aircraft materials. One of the most promising advancements in structures technology is the development of superplastic forming with concurrent diffusion bonding of titanium.

The SPF/DB process is possible because titanium exhibits superplastic properties, and large tensile elongations may be achieved without necking under optimum conditions of temperature and strain rate. Under these same conditions, titanium can be joined by diffusion bonding. This fact allows concurrent SPF/DB to take place in a tool during a single temperature/pressure cycle. This is important in the fabrication of a landing gear outer cylinder since it means that a more structurally efficient truss core sandwich can be made and, in a full strut design, the end fittings, lugs for the torque links and for the side brace can be bonded to the cylinder during the same fabrication cycle.

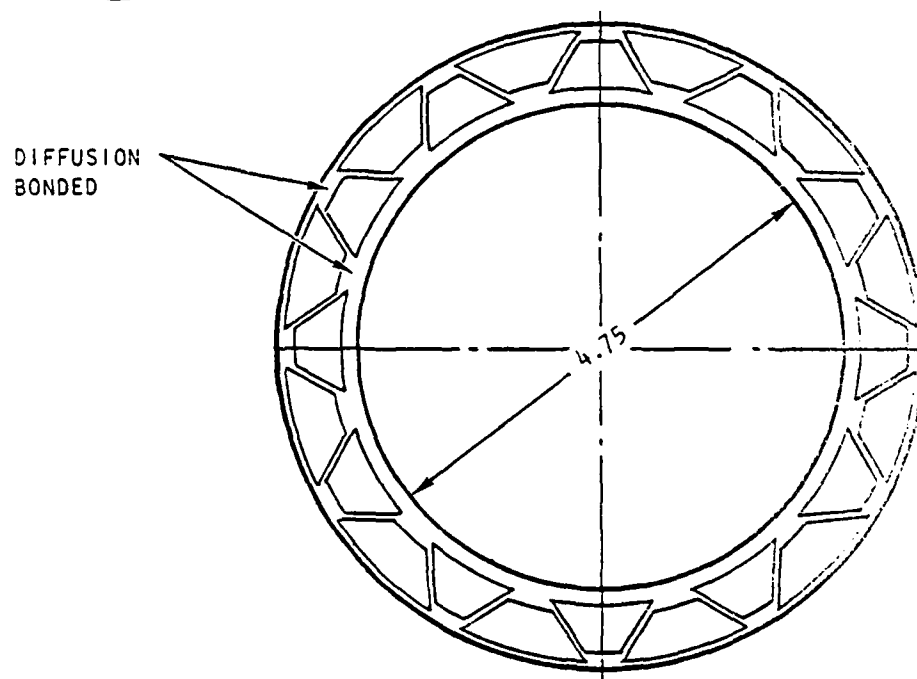
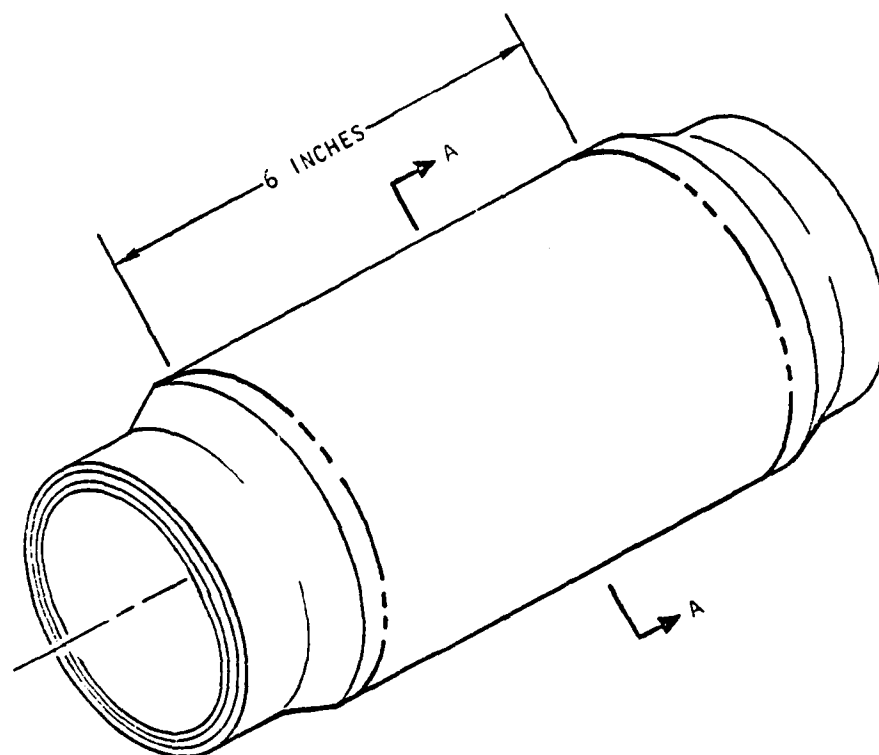
2. OBJECTIVE

The objective of this program was to demonstrate the feasibility of using titanium and SPF/DB fabrication process to design and build a main landing gear outer cylinder and to verify by test that it will satisfy the strength and stability requirements.

3. SUMMARY

The objective of this program has been met by the successful fabrication and testing of a representative section of an existing aircraft landing gear. Using the F-100 fighter aircraft main landing gear as a baseline, a SPF/DB truss core sandwich cylinder, shown in figure 2, was designed to replace the main strut. Critical loads from the original aircraft were used to size the 6 inch representative section of the strut. After an extensive development program which produced a series of breakthroughs in both tooling and fabrication approaches, a successful cylinder shown in figure 3, was fabricated. Compression testing to 158 percent of design ultimate load confirmed the structural integrity of the cylinder.

This program has demonstrated a concept which is projected to produce a weight reduction of 8.4 percent, and reduce the stress-corrosion problem by the use of titanium truss core sandwich struts.



SECTION A-A

Figure 2. SPF/DB Outer Cylinder Section.

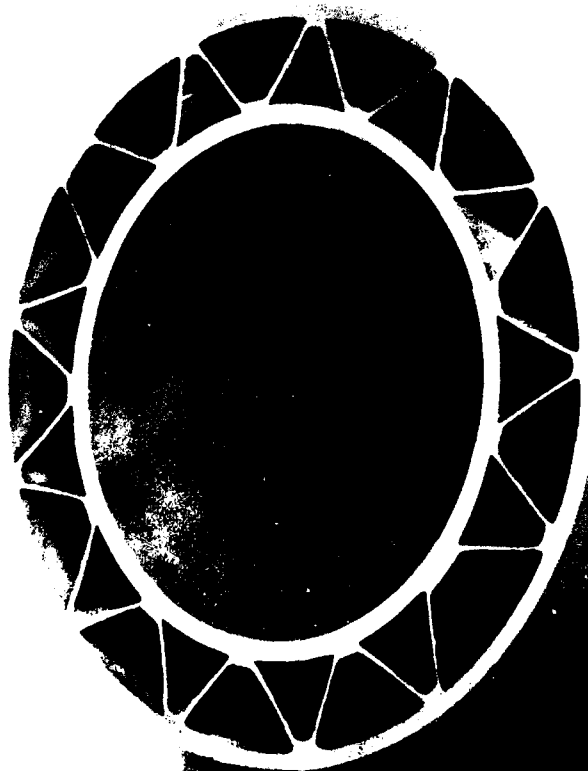


Figure 3. SPF/DB Titanium Outer Cylinder.

SECTION II

PHASE I DESIGN AND DEVELOPMENT

1. BASELINE AIRCRAFT SELECTION

The F-100 aircraft has been selected as the baseline aircraft for this study. This aircraft is an existing fighter with a tricycle landing gear with dual nosewheels and single main gear wheels. The main gear retracts inboard into the fuselage, and the nose gear retracts aft into the nose section. The two main landing gears consist primarily of air-oil-type shock struts with single wheels, see figures 4 and 5.

Each gear pivots on two bearings in the trunnion support fitting on the wing rear spar and is actuated by a hydraulic cylinder attached to the strut below the trunnion and to a wing inboard trailing edge rib. A side brace extends from a lug on the outer cylinder of the strut to a downlock fitting on the wing rear spar and is held in the down position by means of a spring loaded lockpin.

The shock strut is designed with internal metering provisions to control the rate of compression and extension of the piston. The shock struts support the weight of the airplane on a nitrogen and hydraulic fluid cushion which absorbs the landing shock.

The preceding description of the F-100 landing gear could well describe the landing gear on most current first-line fighter aircraft. The structural configuration for landing gears has remained remarkably similar for the 28 years since the F-100 gear was designed.

All design criteria for the landing gear outer cylinder was available for use on the program, since the F-100 was designed and built by NAAD.

The rationale for this selection was presented to the Air Force and approval was given 2 April 1979.

2. MAIN LANDING GEAR OUTER CYLINDER DESIGN

The production drawings and the stress analysis of the F-100 main landing gear were reviewed as a basis for the selection of the part to be fabricated using titanium and the SPF/DB process. The center section of the strut outer cylinder, shown in figure 6, was selected as the part to be fabricated in this program. This section extends from the torque link lug up to the side brace lug, a distance of approximately 12 inches. There are no bosses, lugs, or other fittings in this area of the cylinder. A 6-inch section of this area was redesigned using titanium and the SPF/DB fabrication method, see figure 7.

This section of the F-100 outer cylinder is 4.75-inch inside diameter and has a wall thickness of 0.255-inch. The critical loading condition on this section is due to a two-point braked roll, resulting in no vertical load,

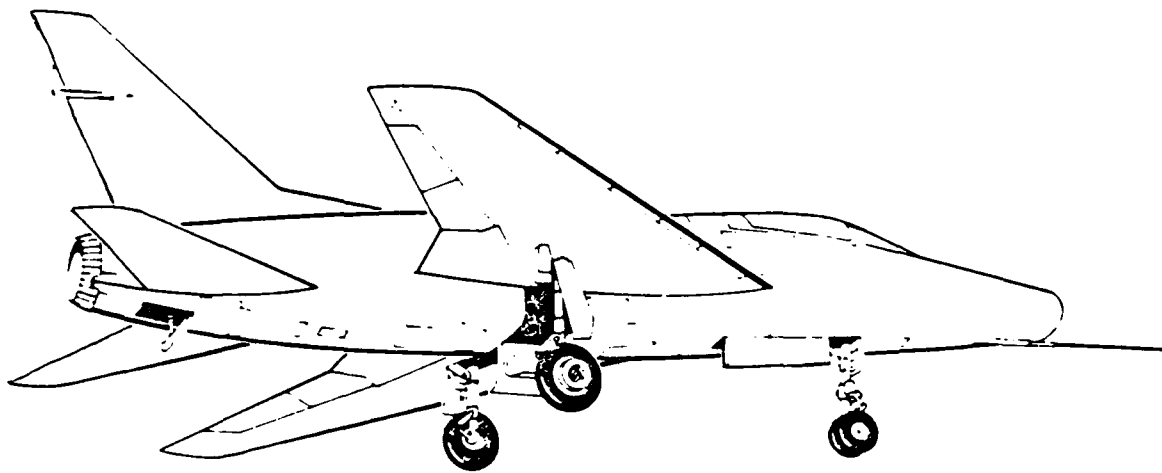


Figure 4. F-100 Fighter Aircraft

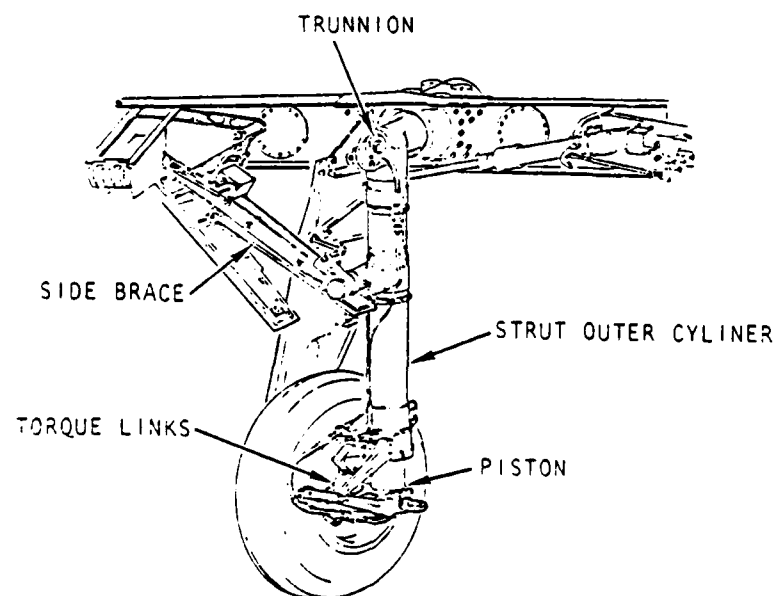


Figure 5. F-100 Main Landing Gear

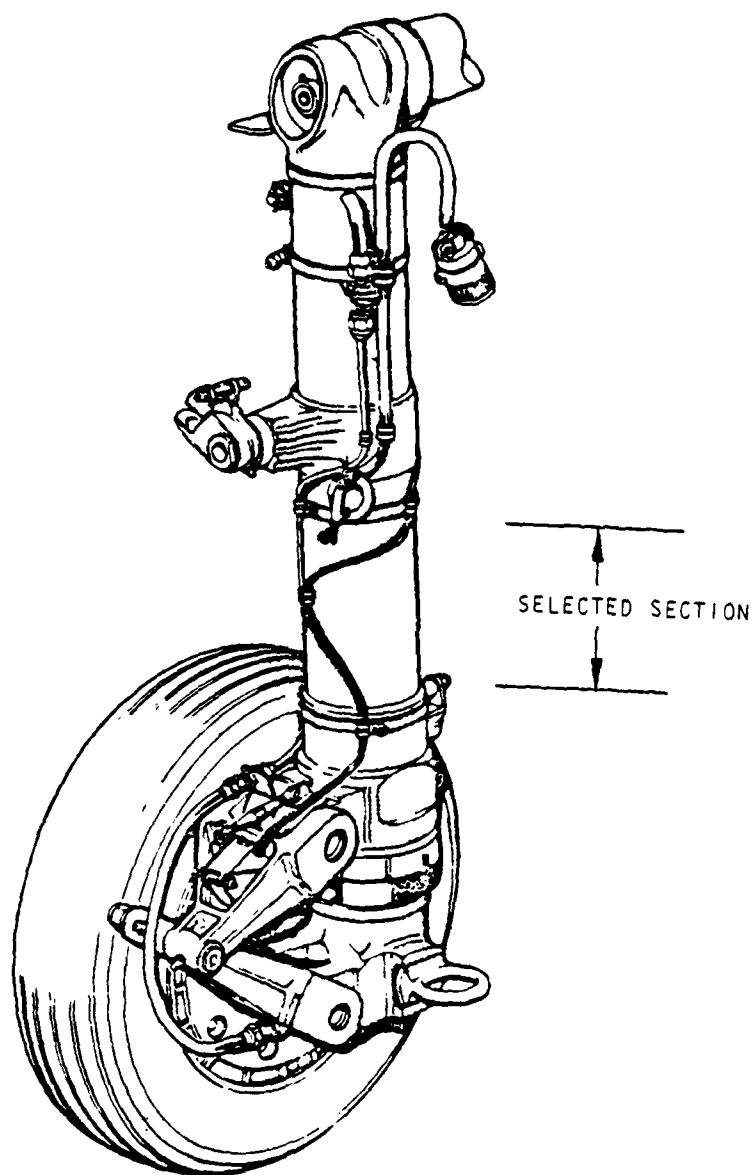
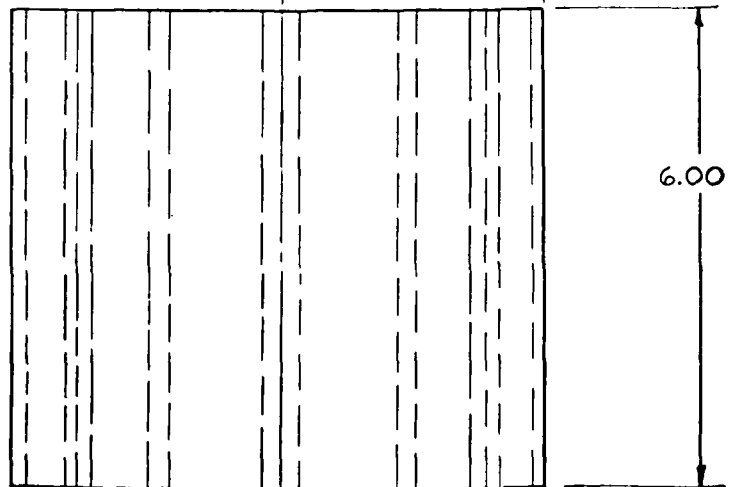
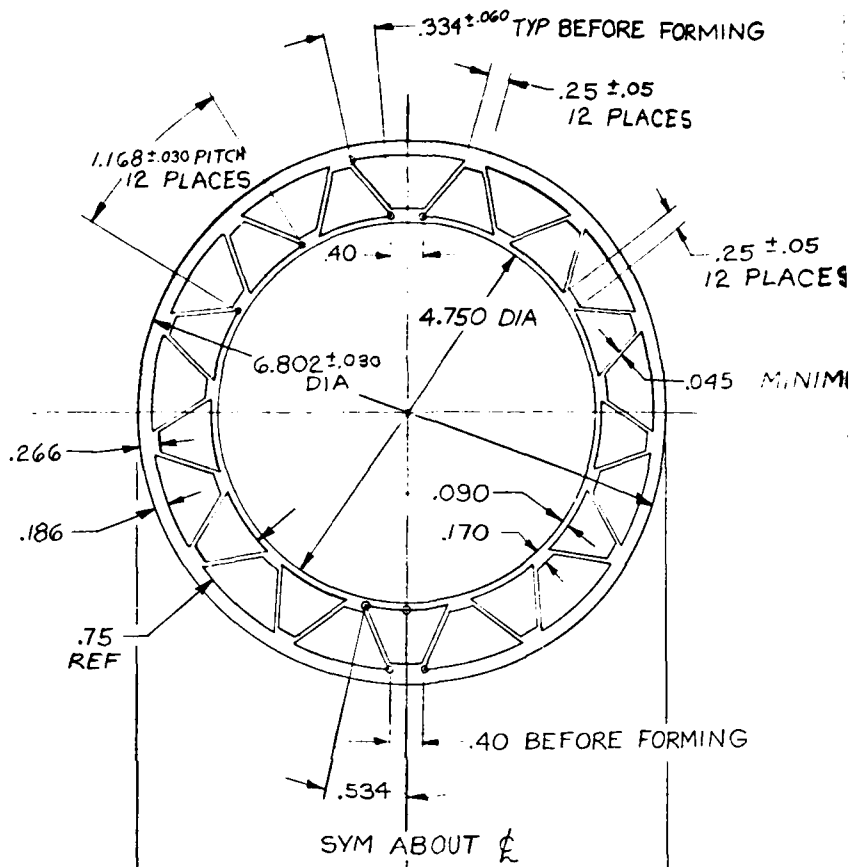
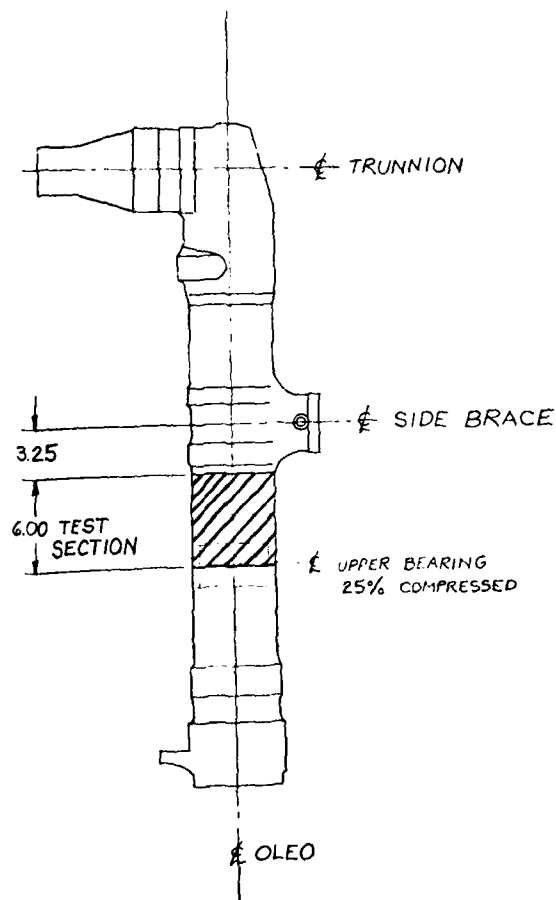


Figure 6. F-100 Landing Gear Strut Section
Selected for this Program



TEST SECTION
SCALE $\frac{1}{1}$



F100 MAIN LANDING GEAR
OUTER CYLINDER
NO SCALE

MATERIAL: 6AL-4V TITANIUM;
MIL-T-9046 CONDA
TOLERANCES EXCEPT AS SHOWN
.X = $\pm .1$.XX = $\pm .03$.XXX = $\pm .010$

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STUDY-TRUSS CORE, OUTER CYL, LANDING GEAR, SPF/DB TITANIUM			D694-1-400

22,617 pound side load, 210,167 inch-pound torque load, and a 1,084,971 inch-pound moment load. The outer cylinder of the strut is fabricated from SAE-4130 steel which is heat treated to 260 to 280 KSI.

A cylindrical truss core sandwich was selected as a most efficient configuration to use for the new design of the outer cylinder. This arrangement improves structural efficiency in that the moment of inertia is increased and the core trusses support the outer cylinder sleeve, see figure 8. These features provide an increased bending modulus and column stability.

It is designed to facilitate SPF DB fabrication and to accommodate expanding the outer sleeve radially outward from the inner sleeve pulling the trusses of the core sleeve into their respective positions. The wider truss core nodes are located where the core sleeve is spliced. The actual assembly of the cylinder back that is placed in the tool for the SPF DB process requires that both the inside cylinder and the outside cylinder consist of two sleeves each. The inside cylinder consists of an inner seam welded sleeve and an outer two piece sleeve. The outside cylinder consists of a seam welded outer sleeve and a two piece inner sleeve, see figure 9. The two piece sleeves are made so that they can be placed on the inside and outside of the core sleeve without sliding on its surfaces. This prevents scraping or smudging the pattern of stop-off material that is applied to the inner and outer surfaces of the core sleeve, see figure 10. This stop-off material prevents bonding of the core sleeve to the inside and outside cylinder except at the nodes during the bonding cycle. Subsequently, the core is formed into trusses during the forming cycle. All of these valves require diffusion bonding at their longitudinal joints that warranted a special task that follows.

3. LONGITUDINAL SPLICE DEVELOPMENT TASK

A longitudinal splice development task was required to assure that the splice joint of the outside cylinder would contain the sandwich expansion pressure after the initial diffusion bonding cycle. The joint must also be capable of superplastic deformation in order to form the sandwich configuration. In addition, a method of splicing the core sheet was needed.

The first step to accomplish this was to fabricate a 9 inch x 9 inch sandwich panel with a full scale truss core cross section incorporating a welded butt joint to represent the outside cylinder splice and a diffusion bonded butt joint to represent the core sheet splice. Fabrication of this part proved that a diffusion bonded bevel lap joint was needed for the core sheet splice, see figures 11 and 12. In order to prove that the butt welder and diffusion bonded outside cylinder splice would work, a second part was fabricated. Two sheets were formed into a deep drawn pan that resulted in over 40 percent elongation transverse to the joint, see figure 13. Since this joint required only 24 percent transverse elongation in the actual cylinder this 40 percent elongation proved that the joint strength was more than adequate.

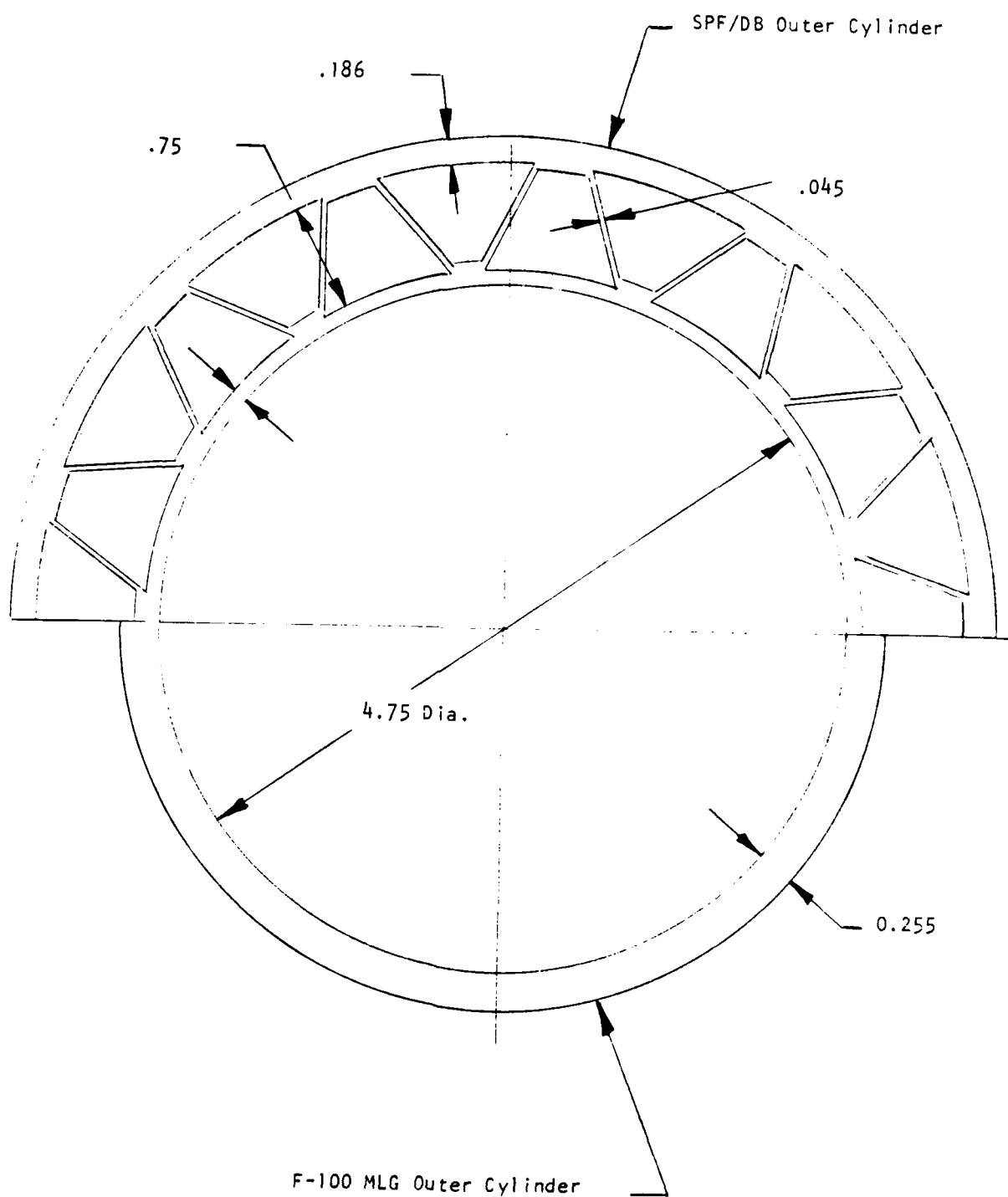


Figure 8. Outer Cylinder Comparisons

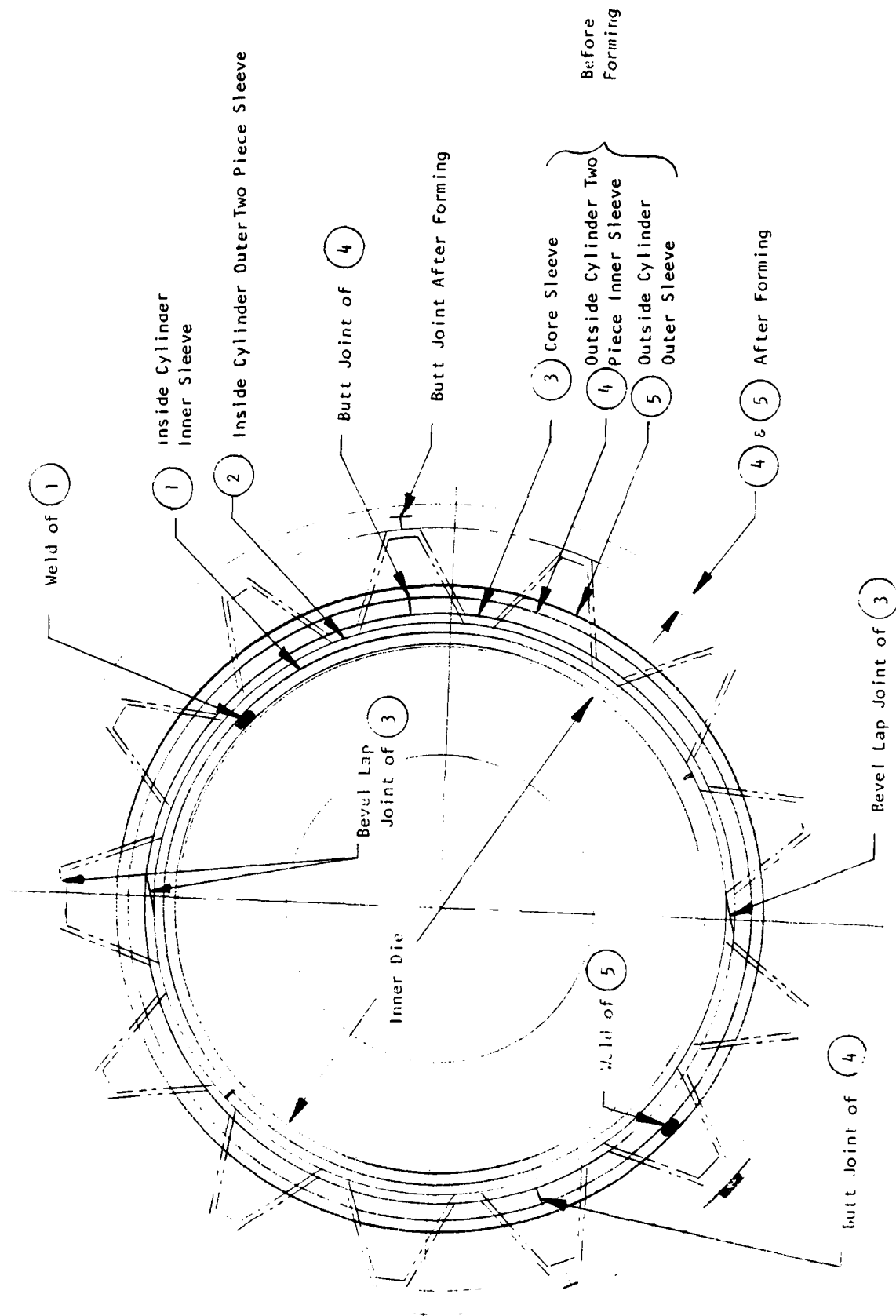


Figure 9. Cross Section of Cylinder Showing the Splices of the Sleeves and Expansion of Outer Sleeves

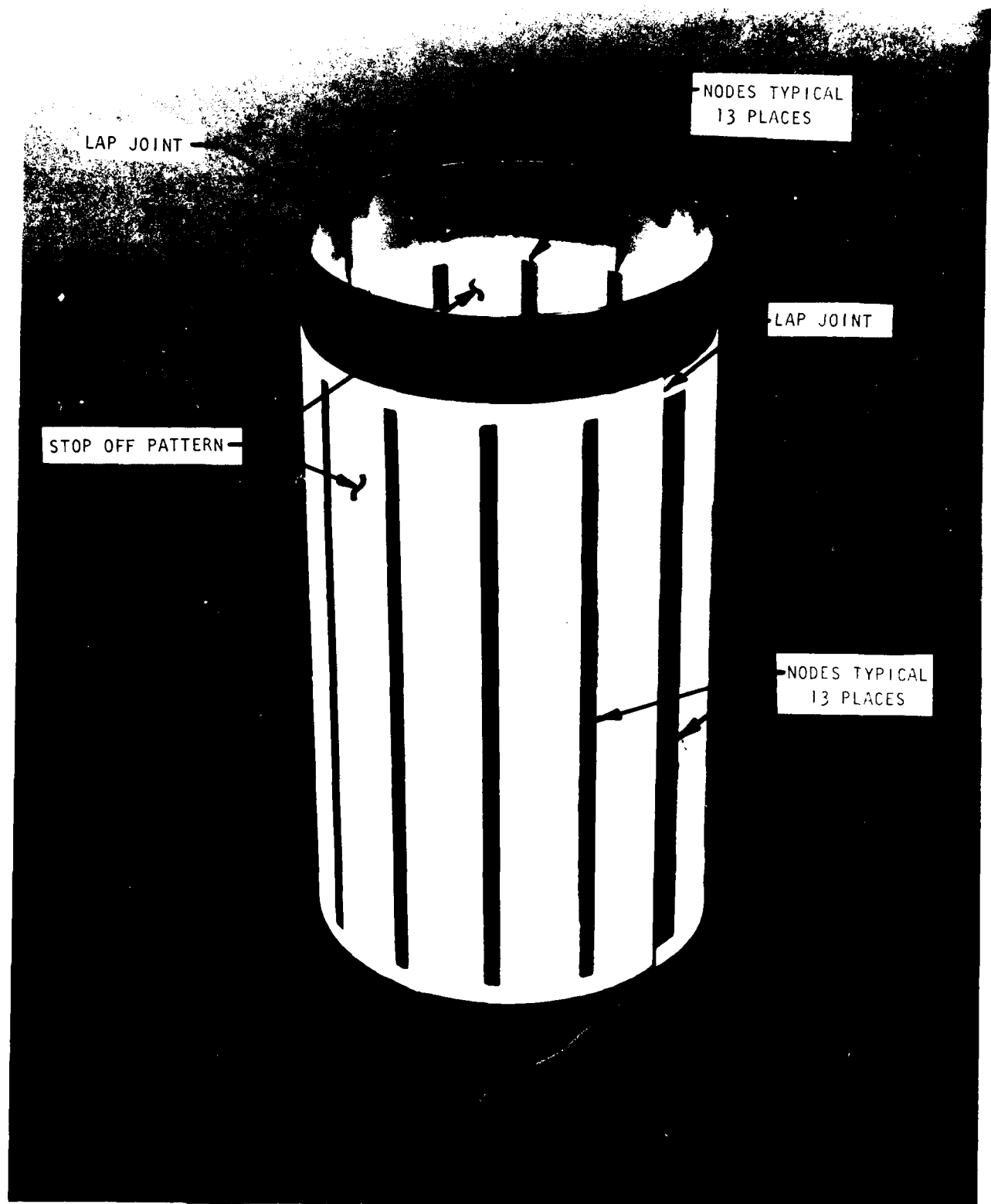
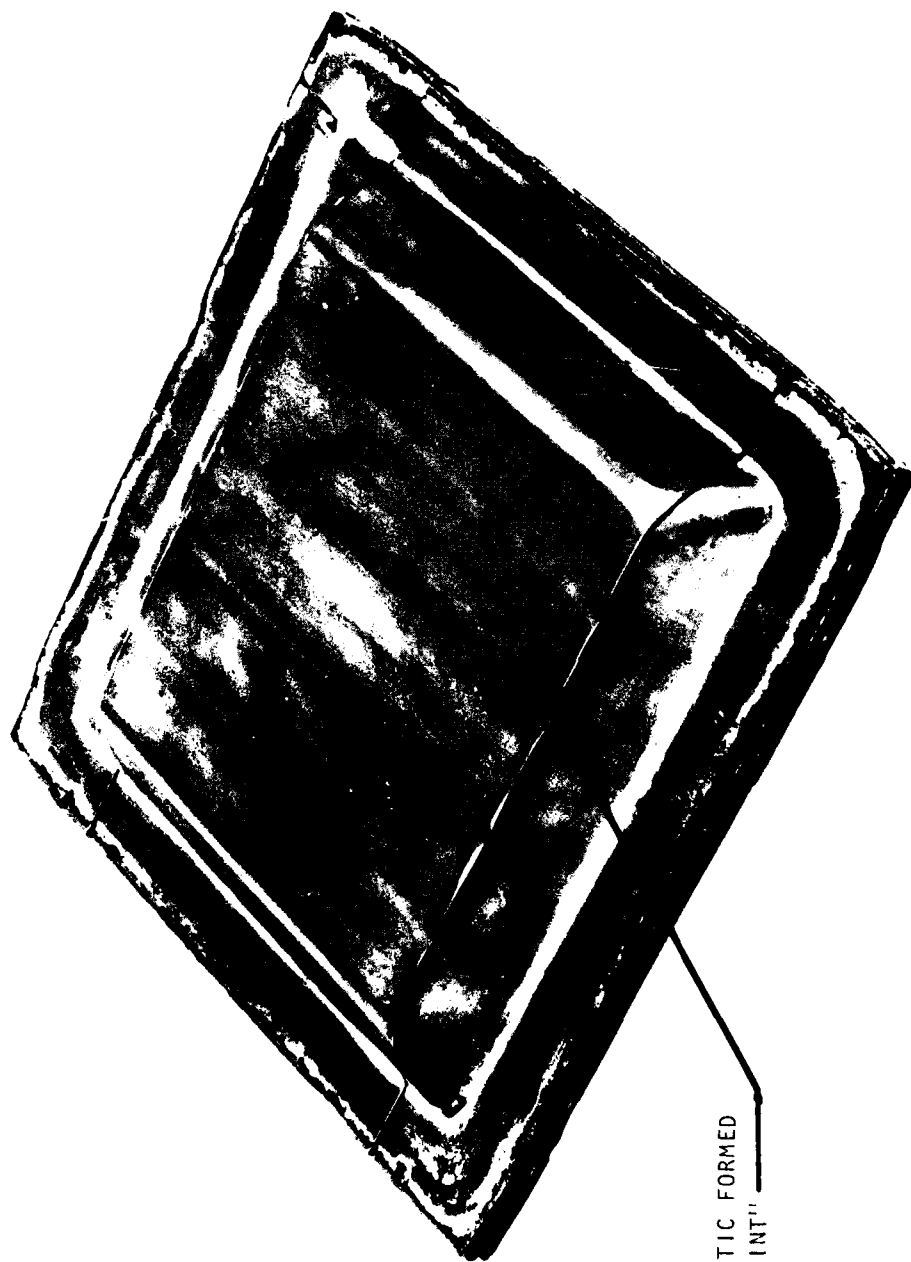


Figure 10. Core Sleeve with Stop-Off Pattern Applied.

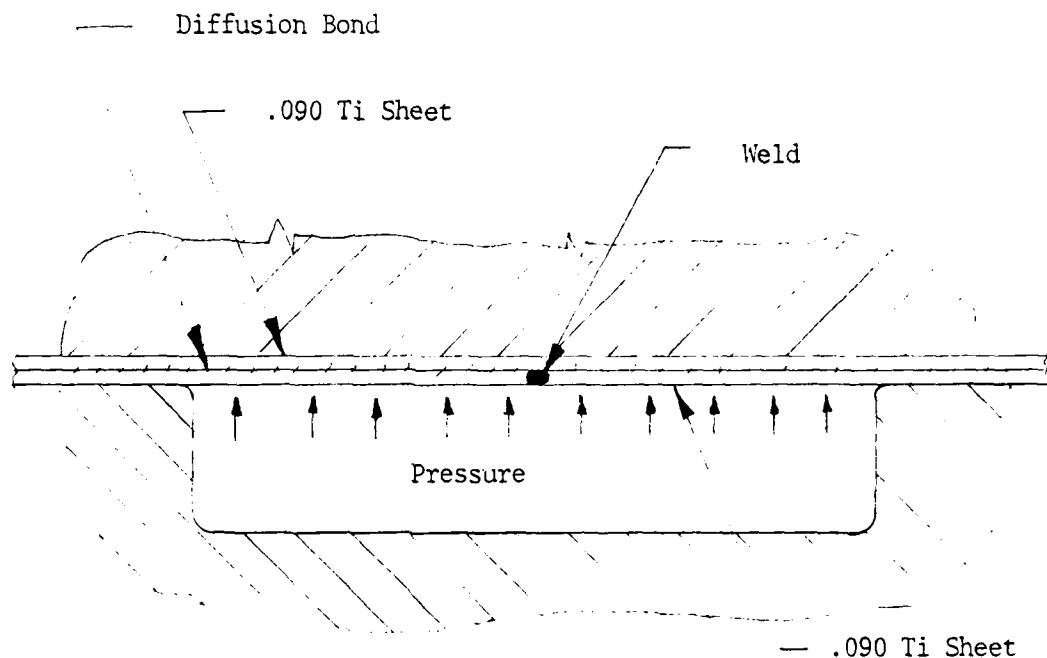


"SUPERPLASTIC FORMED
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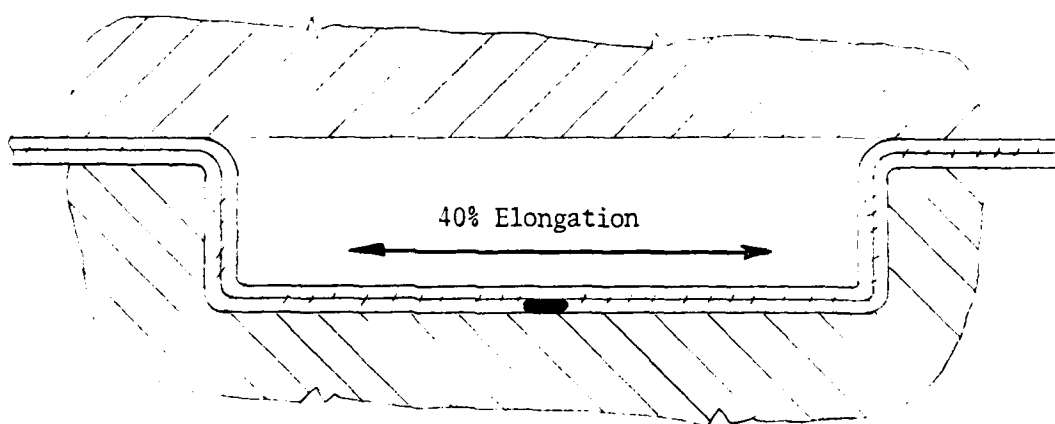
Figure 11. 9 x 9 Inch Panel with SPF Welded Butt Joint.



Figure 12. 9 x 9 Inch Panel Core Sheet Butt Splice.



BEFORE FORMING



AFTER FORMING

Figure 13. Evaluation of Outside Cylinder Butt Welded and Diffusion Bonded Splice

4. STOP-OFF APPLICATION

A stop-off development study revealed that, in order to spray the stop-off material on the inside surface of the core sleeve, the sleeve must be made in two halves. For future parts it was decided that chem-milling a recess into the surface where it is desired to have the stop-off remain, would permit sliding the inner and outer sleeves over the core sleeve without disturbing the stop-off. This feature would eliminate the necessity of having the additional two piece sleeves for both the inboard and outboard cylinders.

5. TOOLING DEVELOPMENT CIRCUMFERENTIAL SEAL

A circumferential seal was required for each end of the cylinder to hold pressure for both diffusion bonding and forming. Tapered plugs were designed to press inside the ends of the cylinder and obtain a seal by squeezing the ends of the cylinder pack against the inside of the tool. In practice this did not prove adequate. So a diaphragm (titanium sleeve), was incorporated to provide sealing, see figures 14 and 15.

6. STRESS ANALYSIS AND WEIGHT STUDY

A structural analysis was made to size the SPF/DB cylinder. Thickness requirements for the inner and outer sleeve, and the truss core were calculated. The core height and the node spacing was optimized. The most critical load on the selected section of the F-100 landing gear outer cylinder was used. A conservative F_y allowable of 117,000 psi was used resulting in a margin of safety of +.002. A detail analysis is given in Appendix A.

A weight calculation was then made which showed that the SPF/DB cylinder weighed 1.0388 lbs/in compared to 1.1347 lbs/in. for the existing steel cylinder. These figures show a weight saving of 8.45 percent.

7. TOOL DESIGN

A tool design drawing was prepared for making the tools. Tools were required for hot sizing the sleeve halves and for SPF/DB the cylinder.

8. AIR FORCE APPROVAL

Air Force approval was given for go-ahead with phase II after all requirements of phase I were met. Air Force approval of test plan and the the final test was also given.

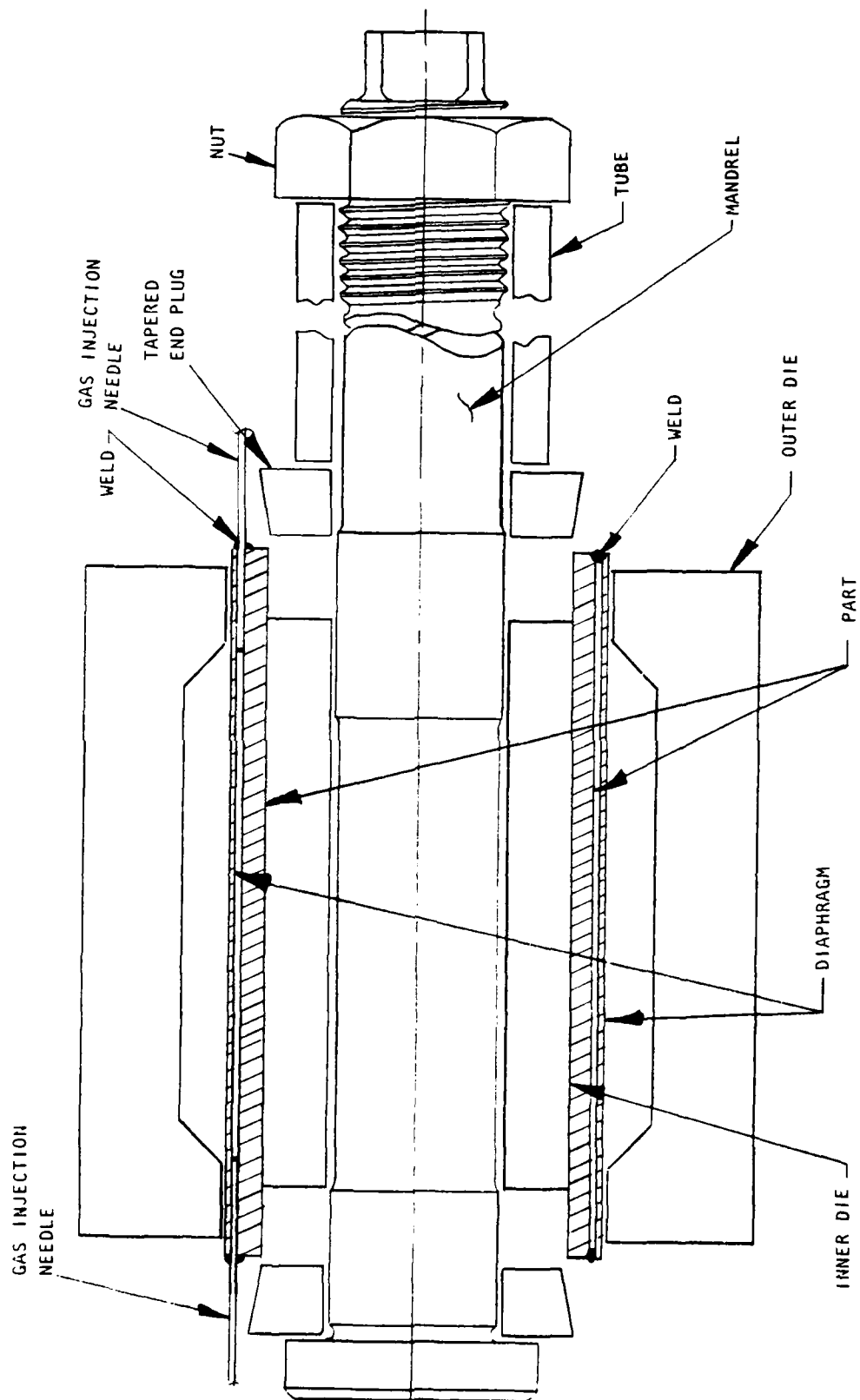


Figure 14. MLG SPF/DB Titanium Outer Cylinder Segment Assy with a Diaphragm Seal for DB Cycle.

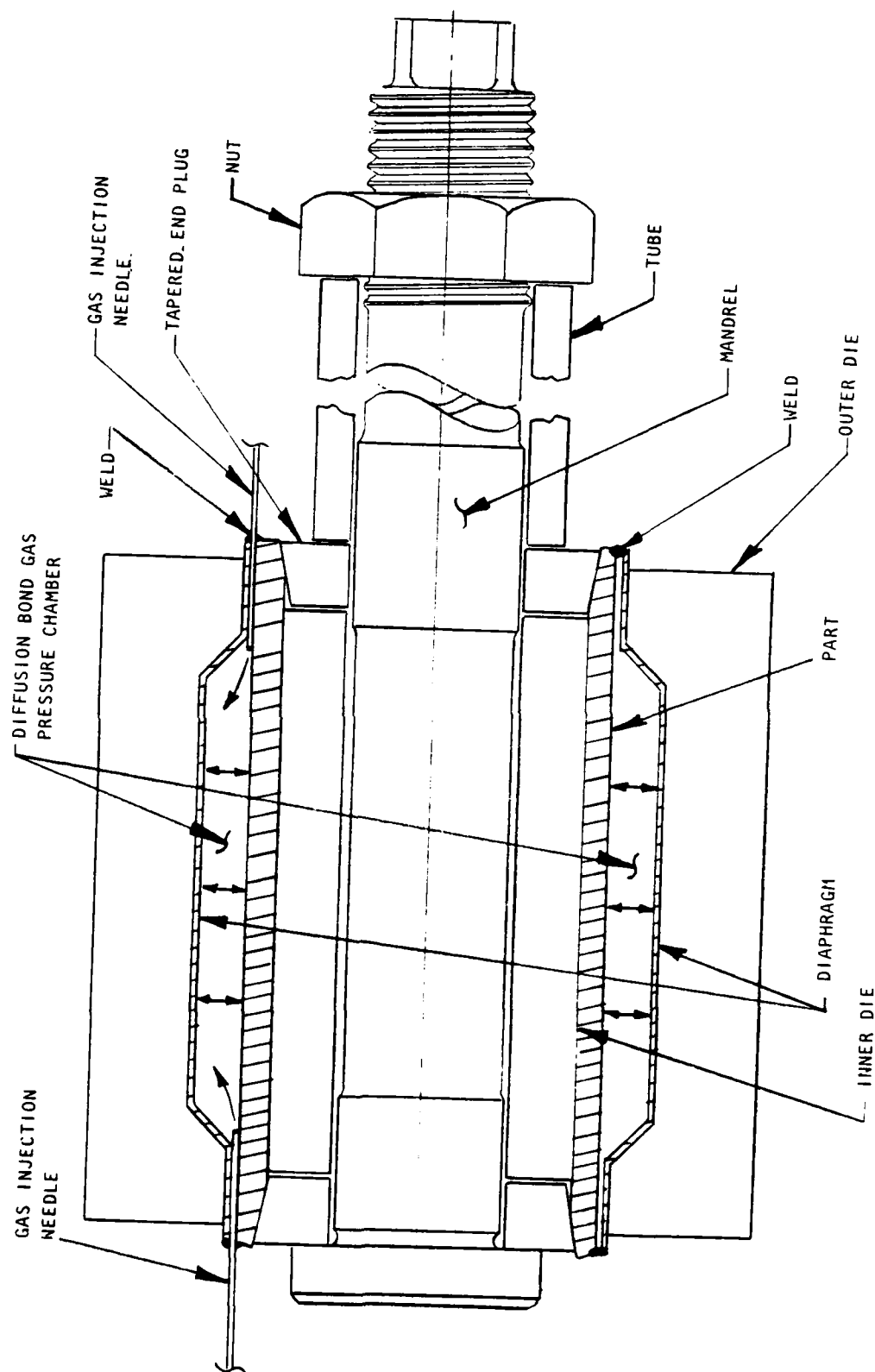


Figure 15. MLG SPF/DB Titanium Outer Cylinder Segment DB Cycle Using a Diaphragm Seal.

SECTION III

PHASE II - FABRICATION AND INSPECTION

1. TOOL FABRICATION

a. HOT FORMING DIE

A hot sizing tool was required for preforming the inner and core sleeve halves, see figure 16.

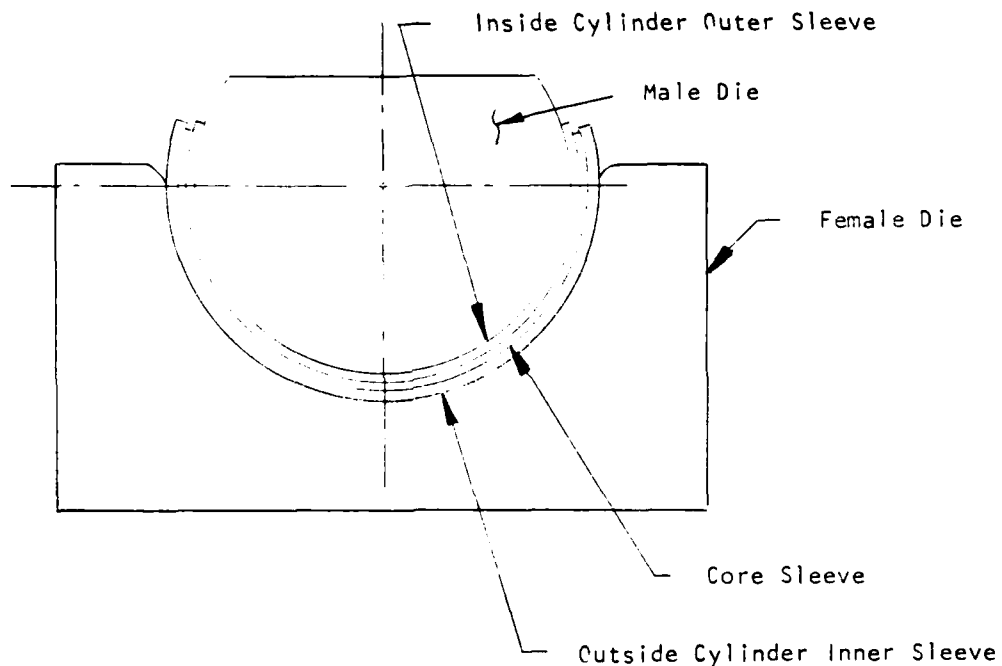


Figure 16. Hot Sizing Tool

Figure 17 shows a sleeve half partly removed from male die.

b. CYLINDER TOOL

The cylinder tool consists of a two piece female die, inner mandrel (inner die), two tapered end plugs and a long mandrel having a head on one end with threads at the other end similar to a large bolt. At the head of this mandrel the dies, the "pack", (which will be formed into the cylinder), the inner die and the tapered plugs are held in place with a large special



Figure 17. Semi Circular Laminate Hot Forming Die.

nut on the threaded end of the long mandrel with the spacer tube between the nut and one of the tapered plugs. See figure 18. This arrangement permits torquing the nut to apply pressure on the tapered plugs when the pack is in the press with the heat turned on. Figures 19 and 20 show these tools with some of the sleeve halves.

2. OUTER CYLINDER FABRICATION

a. PRODUCIBILITY DEVELOPMENT

The first attempts to fabricate a cylinder failed due to leakage of the seal cavity which prevented diffusion bonding of the pack. See figure 21. Several changes were made such as modifying the parting surface wire seals that fit in a groove on the lower die and the bevels for these wires at each end of the dies. See figures 22 and 23. Reducing the length of the inner cylindrical die to allow more travel for the tapered plugs and adding shims to the surface of the tapered plugs was tried, but even though as much as 200 psi pressure was obtained, it was not enough for a good seal. Forming was attempted in spite of an inadequate bonding cycle, but at 100 psi a leak around the gas inlet tubes developed. Within two hours the outlet pressure deteriorated to 60 psi while inlet pressure was maintained at 300 psi. Partial forming of the cylinder was the result.

A diaphragm was then added to enclose the pack to insure a positive seal. See figures 24 and 25. The diaphragm seal was successful and diffusion bonding was accomplished, but when forming was tried there was a lag in the forming inlet and outlet pressures indicating a leak which was found to be at the core gas injection tubes. The pack was removed and its ends were welded closed, including the area around new gas injection tubes. See figures 26 and 27. The pack was again placed in the dies and fabrication resumed, but at 100 psi forming pressure a leak was detected between the diaphragm and the outer face sheets indicating a rupture in the part.

After the part was sectioned and the diaphragm removed, the rupture became visible. See figure 28. The butt joints of the outside cylinder inner sleeve face sheets did not sufficiently bond to resist the expansion stress across the joint during forming and the gas pressure subsequently ruptured the outer sleeve of the cylinder. See figure 29. However, the core bevel splices appeared to be bonded. See figures 30 and 31. Therefore, the bevel splice configuration was applied to all butt joints. Inserts to accomplish this were required because the outside inner sleeve halves were already fabricated to size. See figure 32.

The fifth attempt to fabricate a cylinder was successful except that one truss member of the 26 members ruptured. Close inspection and evaluation

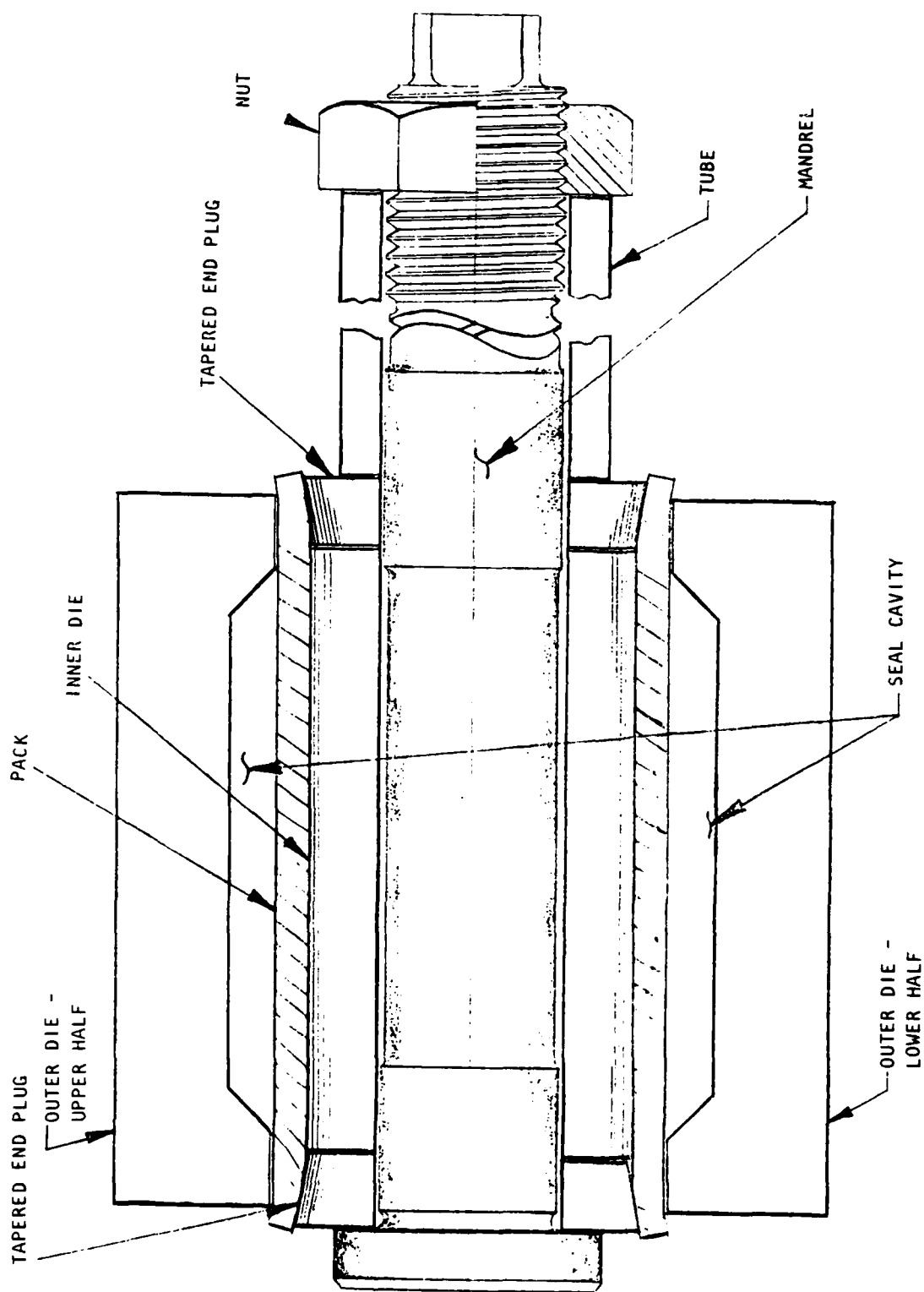


Figure 18. Main Landing Gear SPF/DB Titanium Outer Cylinder Segment Fabrication.



Figure 19. Landing Gear Cylinder SPT/DB Outer Die Half.



Figure 20. Landing Gear Cylinder SPF/DB Tool with Semi-Circular Laminar.

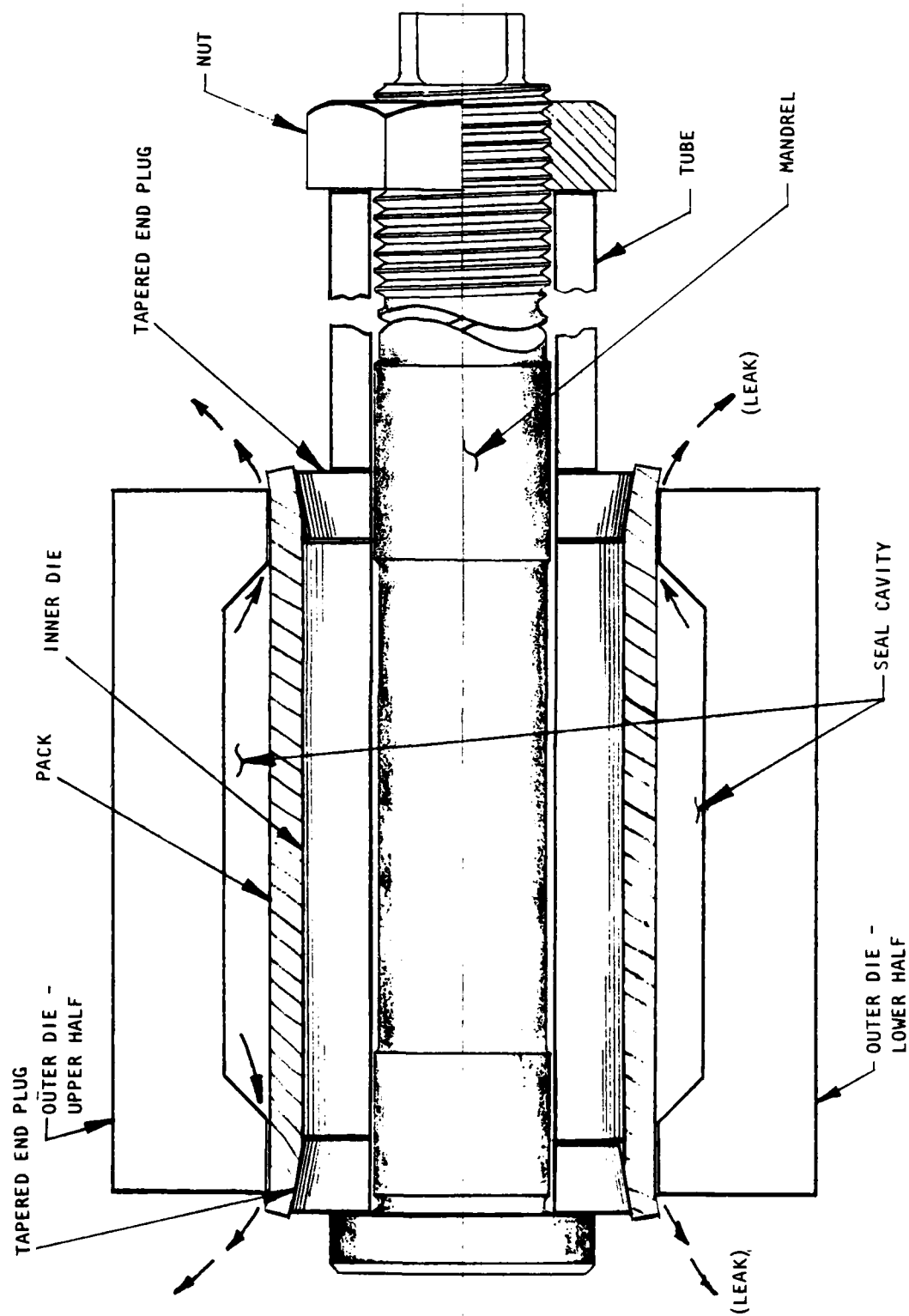


Figure 21. Main Landing Gear SPF/DB Titanium Outer Cylinder Segment Fabrication.

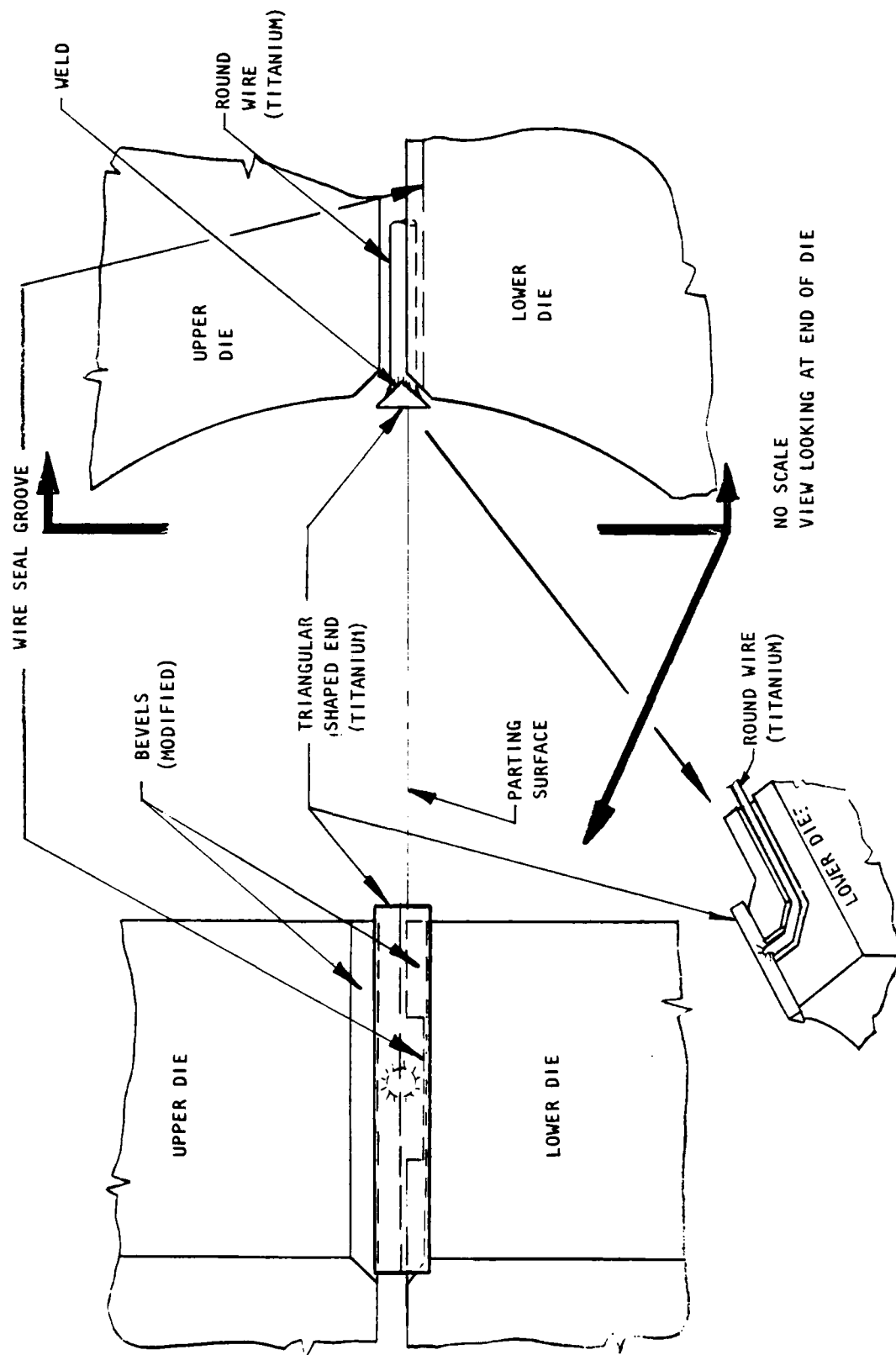
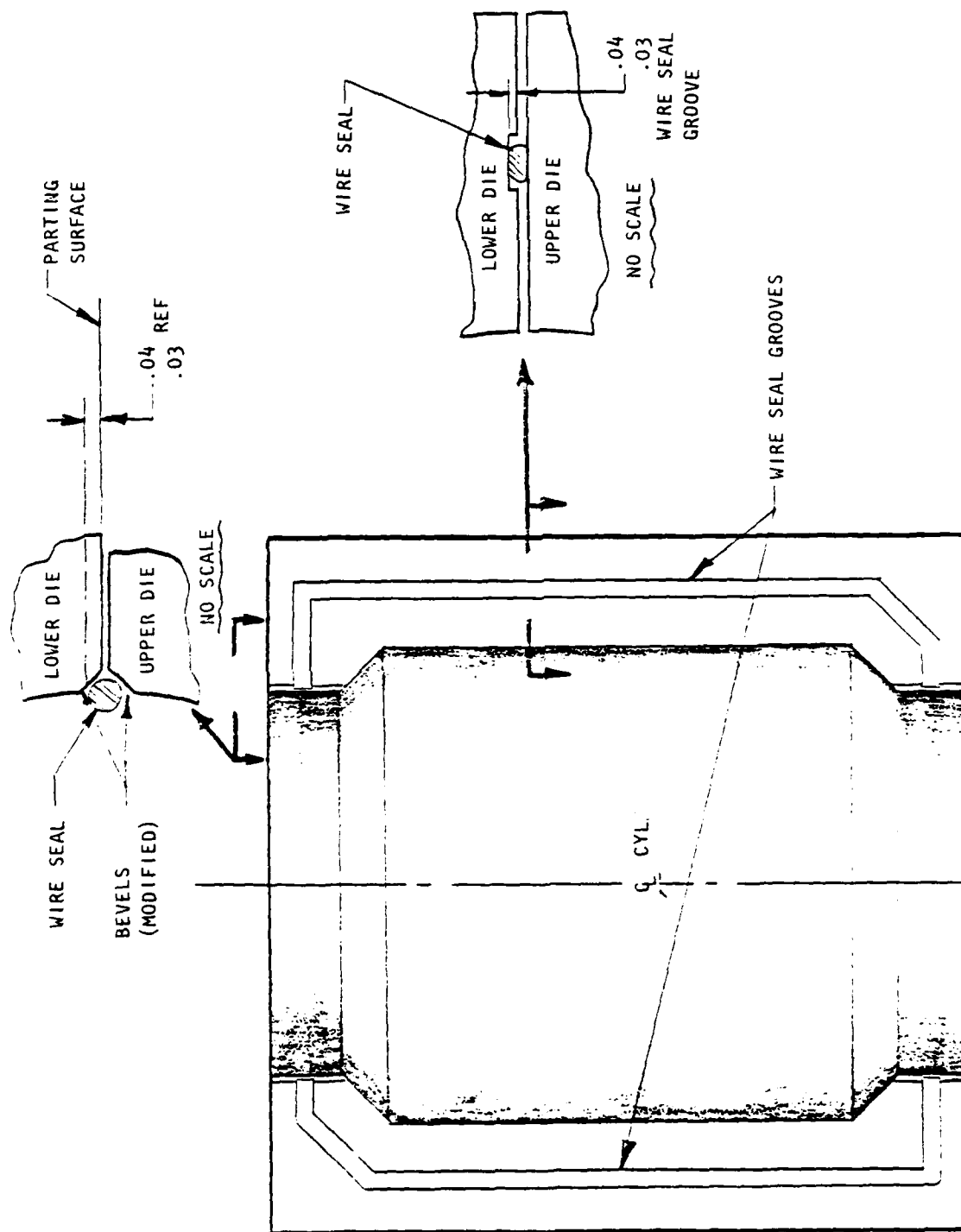


Figure 22. Detail of Modified Wire Seal.



VIEW LOOKING DOWN ON PARTING SURFACE OF LOWER DIE
Figure 23. MLG SPF/DB Titanium Outer Cylinder Segment Tool.

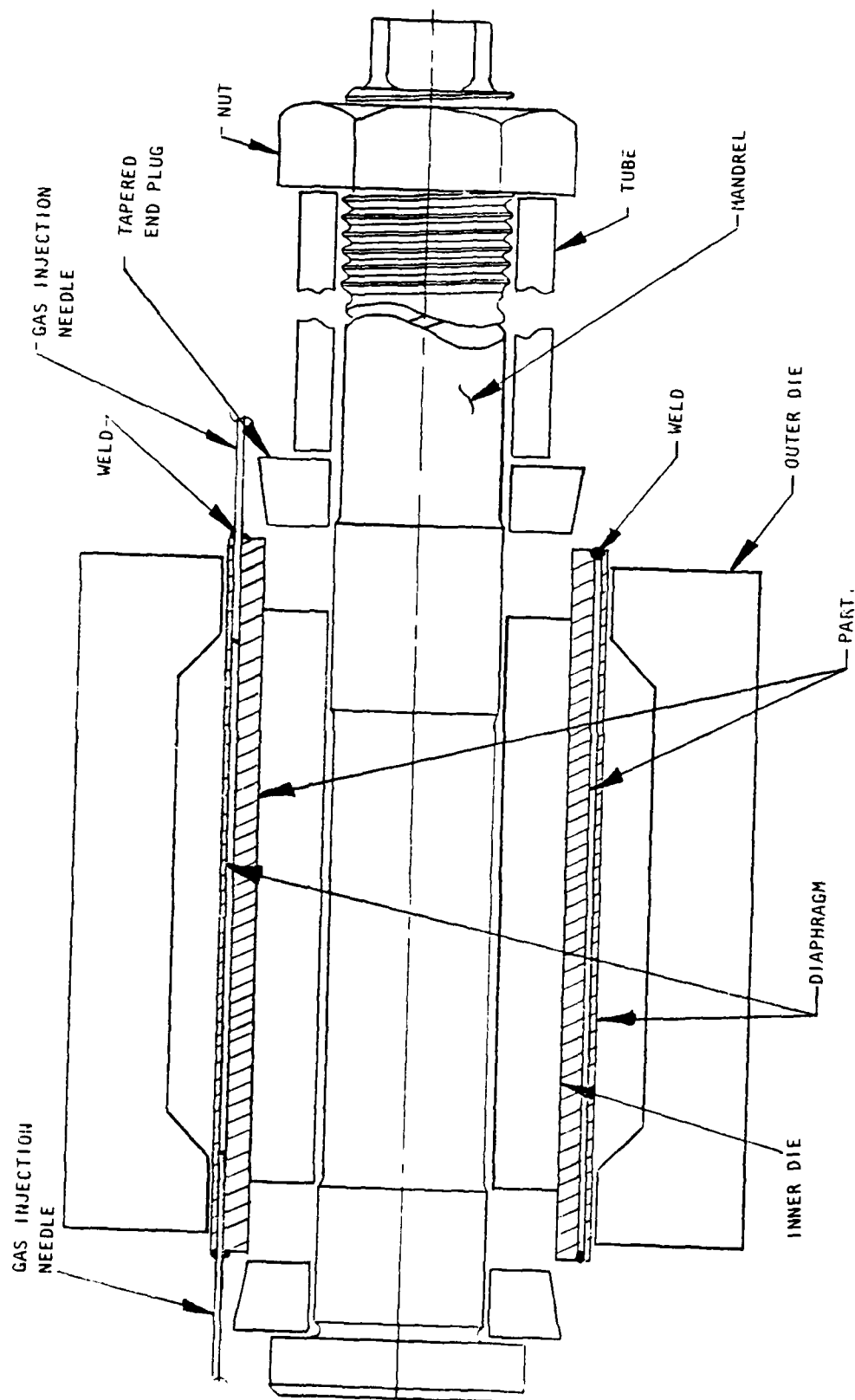


Figure 24. MLG SPF/DB Titanium Outer Cylinder Segment Assy with a Diaphragm Seal for DB Cycle.

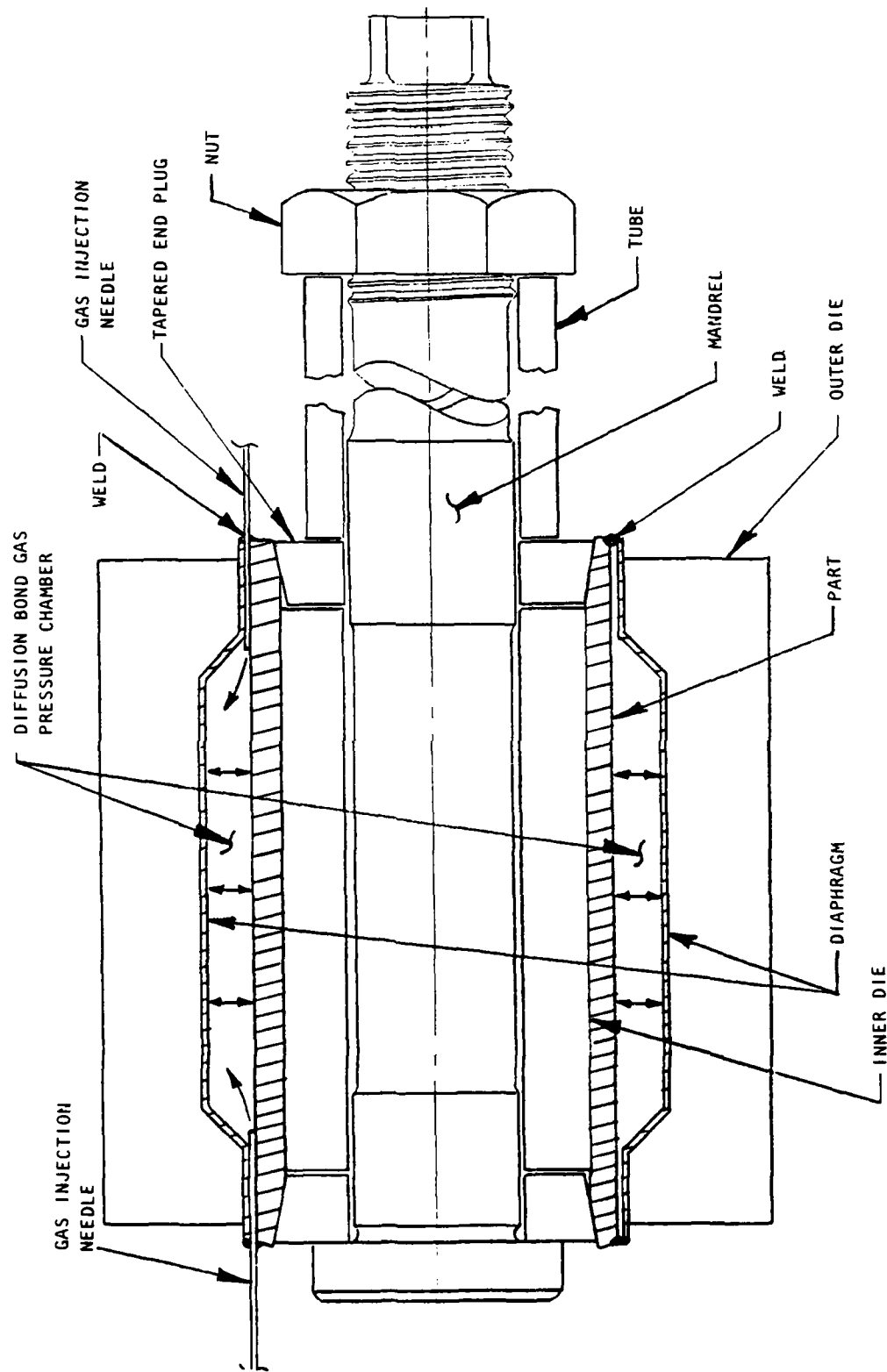


Figure 25. MLG SPF/DB Titanium Outer Cylinder Segment DB Cycle Using a Diaphragm Seal.



Figure 26. Cylinder Segment with Expanded Diaphragm.



Figure 27. Cylinder Segment with Ends Welded Closed Before
Installation of New Injection Tubes





Figure 29. Butt Joints of the Inner Sleeve of Outer Face Sheets Insufficiently Bonded.

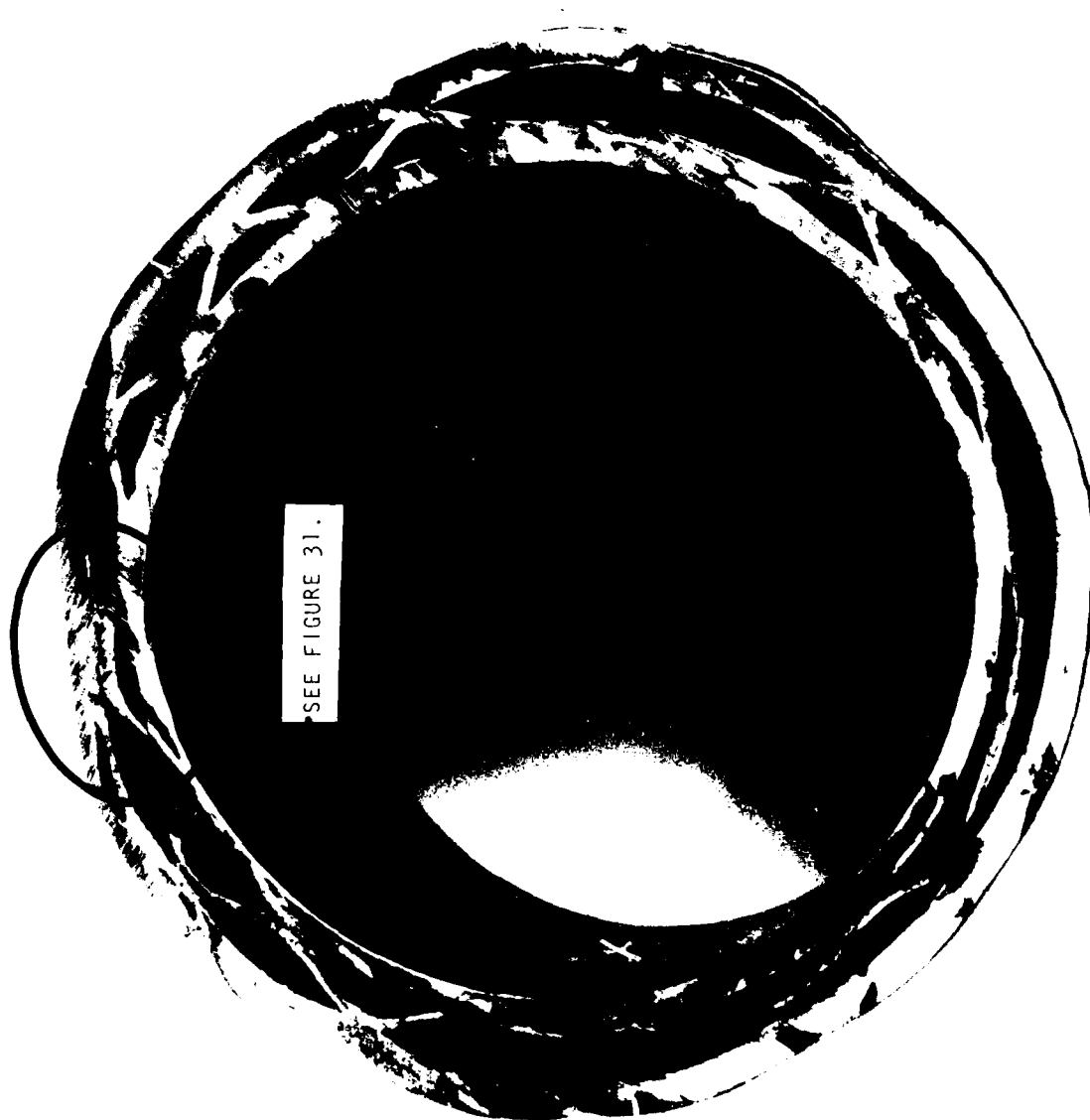


Figure 30. End View of Cylinder Segment Showing Bond of Core Bevel Splice.

CORE SLEEVE
BEVEL SPLICE

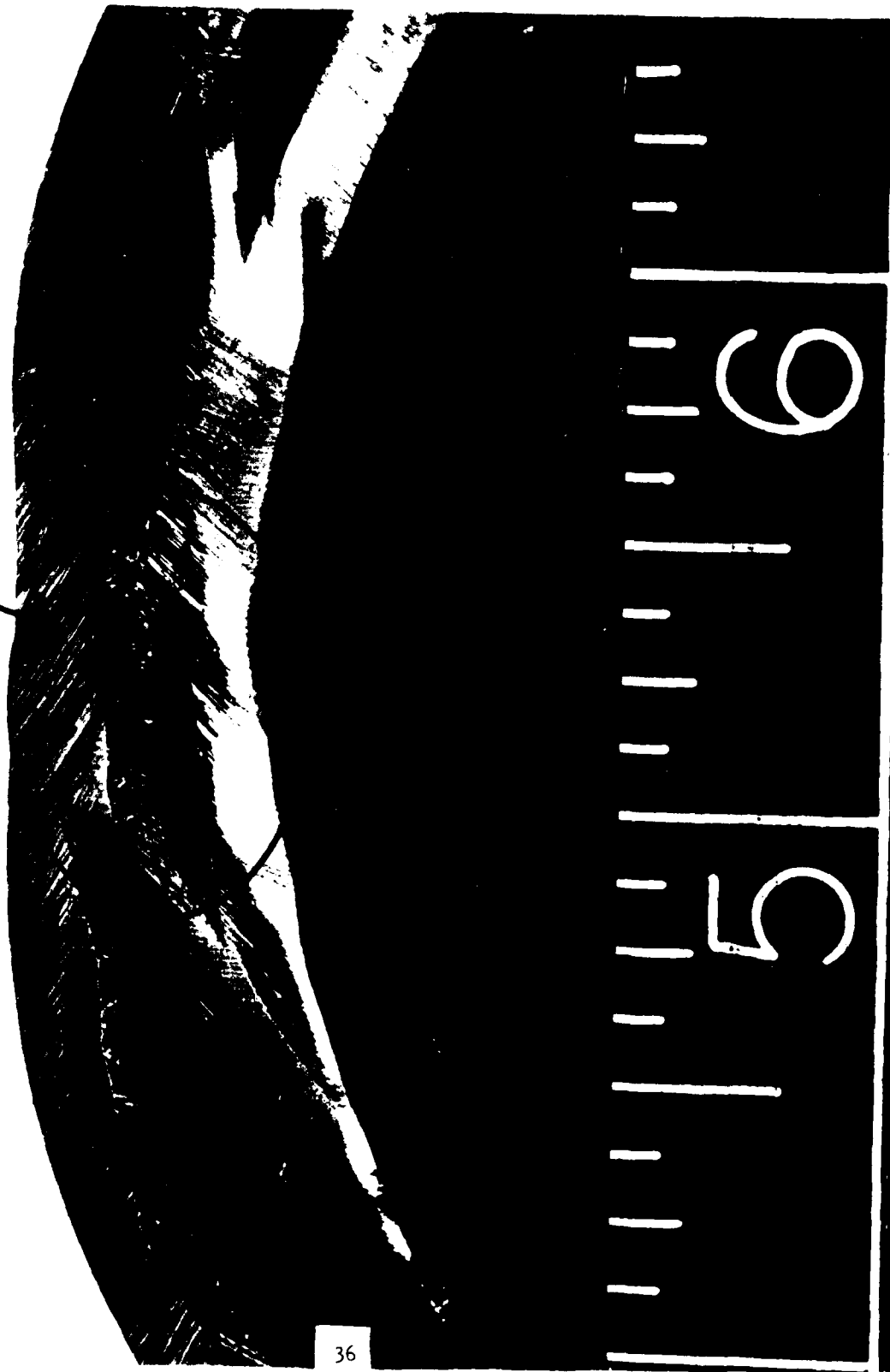


Figure 31. Magnified View of Successful Bond of Core Sleeve Bevel, Splice.

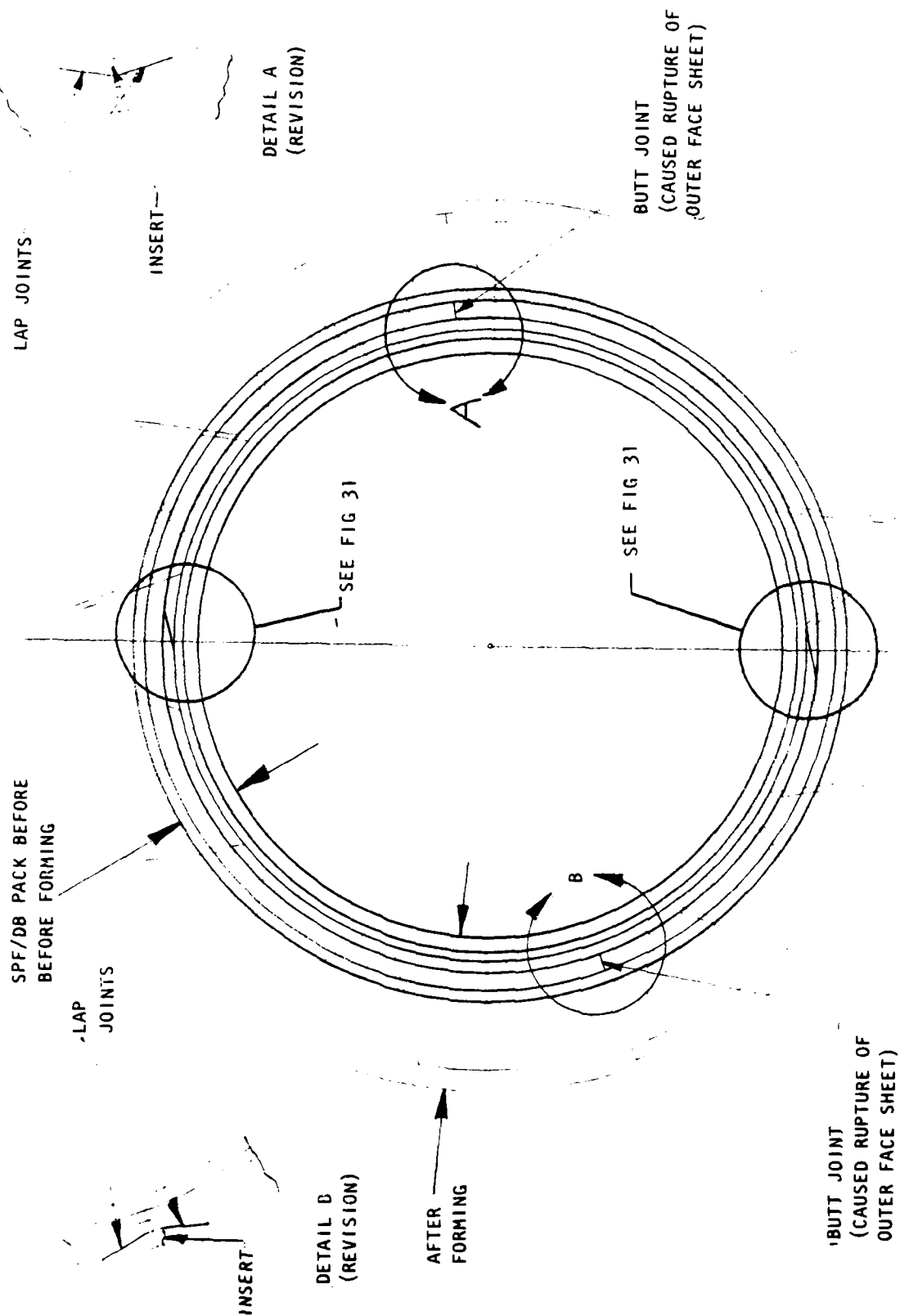


Figure 32. SPF/DB Landing Gear Cylinder Outer Face Sheet Butt Joints Revised to Lap Joints.

indicated that one of the core sheet bevel joints was misaligned causing the rupture. This was corrected on the next attempt by modifying the stop-off pattern to widen the nodes located at these bevel joints and to make the joint less critical to misalignment. More emphasis was placed on checking core sheet bevel joint alignment in the pack inspection procedures.

b. SUCCESSFUL FABRICATION OF CYLINDER

The sixth attempt to fabricate a cylinder was successful. No problems were encountered throughout the SPF/DB process cycles. The outer cylinder fully formed and when the ends were cut off the internal core structure was found to be fully formed and bonded. The core trusses were even and straight with no ruptures. See figure 33.

The inside diameter was cut to size leaving the inner wall thickness as specified by the engineering drawing. The outer cylinder and truss core were left as formed because they were to drawing specifications. The ends of the cylinder were ground flat and normal to the cylinder axis.

3. CYLINDER INSPECTION

The cylinder passed ultrasonic and die penetrant inspections. Visual and dimensional inspections confirmed that the part was acceptable and ready for testing. Figure 34 shows the finished dimensions of the specimen.



Figure 33. SPF/DB Titanium Landing Gear Cylinder Segments,
No. 5 Shown at Left, No. 6 Shown at Right.

Dimensions on end of Cylinder

Dimensions in Parenthesis () are on opposite end of Cylinder

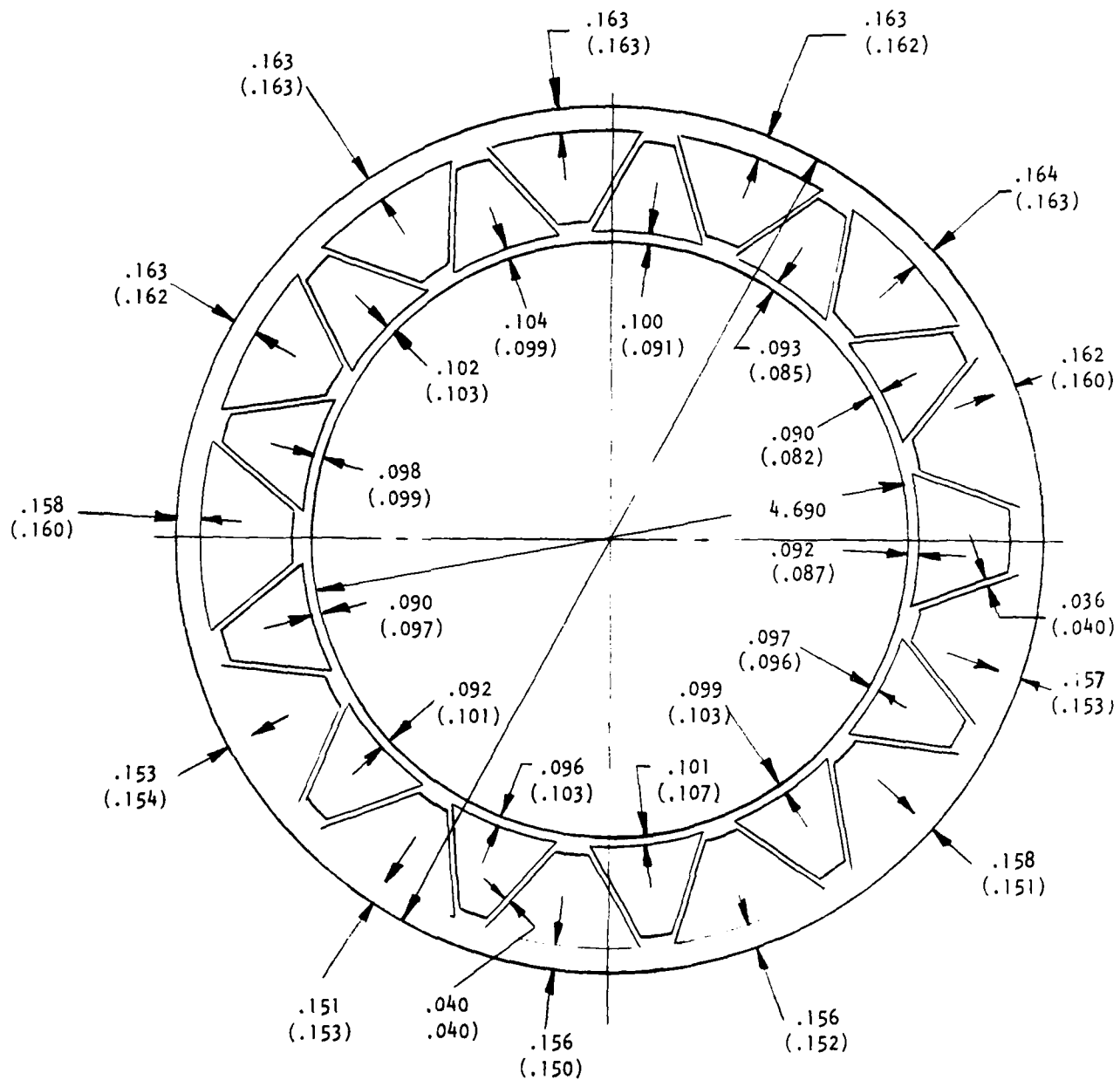


Figure 34. Dimensions of Test Specimen - Inspection Record

SECTION IV

PHASE III - TEST

1. TEST PLAN AND AIR FORCE APPROVAL

A test plan (Appendix B) to verify that the SPF/DB titanium outer cylinder segment satisfies the strength and stability requirements for the F-100 main landing gear was written, submitted and approved by the Air Force on 26 September 1979.

Since compression stress is the critical condition, a straight axial compression test was planned in lieu of a more expensive bending test. The design axial compression load of the cylinder 6.0 inch segment is 600,000 lbs. The load was to be continually increased until the specimen failed.

2. TEST

The test was conducted at the Rockwell Structures Lab on 9 April 1980. Axial strain gages and radial deflection instrumentation were installed on the specimen and the test was performed in a 1,000,000 lb. capacity press. Eight axial strain gages were installed. Four were mounted on the middle of the cylinder outer surface spaced 90° apart with four mounted directly opposite on the cylinder inner surface. See figure 35.

The load was continually increased in increments of 50,000 lbs. with readings recorded at each step. The highest recorded axial strain was at 850,000 lbs. where instrumentation failed. The maximum recorded radial deflection readings at the four locations were at 900,000 lbs. The cylinder failed at 948,000 lbs. and the applied load was immediately released.

3. TEST RESULTS

The test was successful in that the results proved the cylinder design configuration is capable of carrying compressive loads up to the compressive yield values of the material without buckling. An average of the eight axial strain gages at a load of 850,000 lbs. was 11,313 micro inches (.011313 inches). See figure 36. The load divided by an average of the areas of both ends of the cylinder was: $850 \text{ KIPS} / 6.113 \text{ in}^2 + 6.083 \text{ in}^2 / 2 = 139,390 \text{ psi}$ compressive stress. The radial deflections at 850 KIPS were at location: A = .1506 in; B = .0937 in; C = .0802 in; D = .1360 in. The maximum radial deflections obtained were at 900 KIPS. They were A = .2392 in; B = .1494 in; C = .117 in; D = .2099 in.

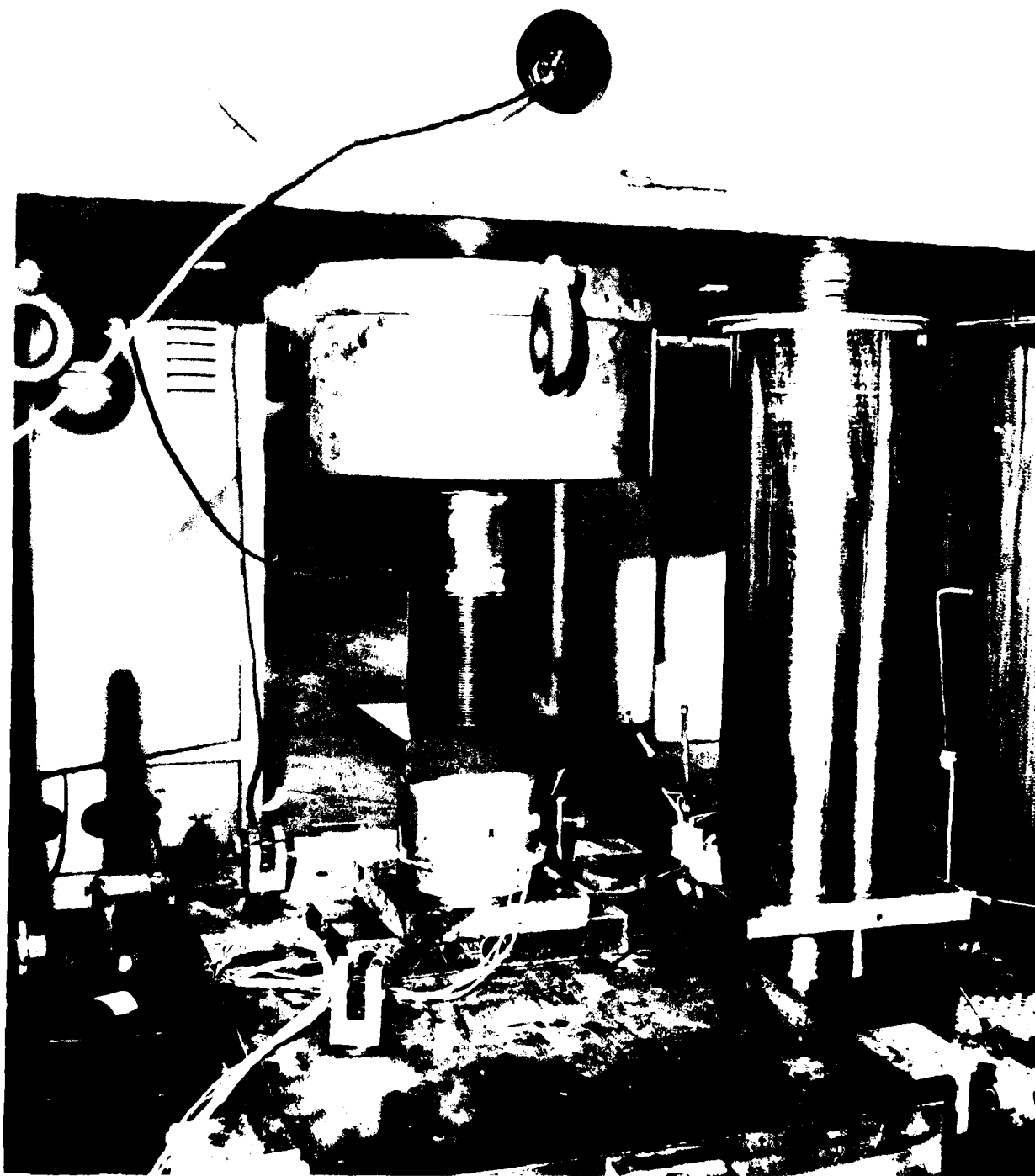


Figure 35. SPF/DB Titanium Truss Core Cylinder in 1,000,000 lb. Capacity Press.

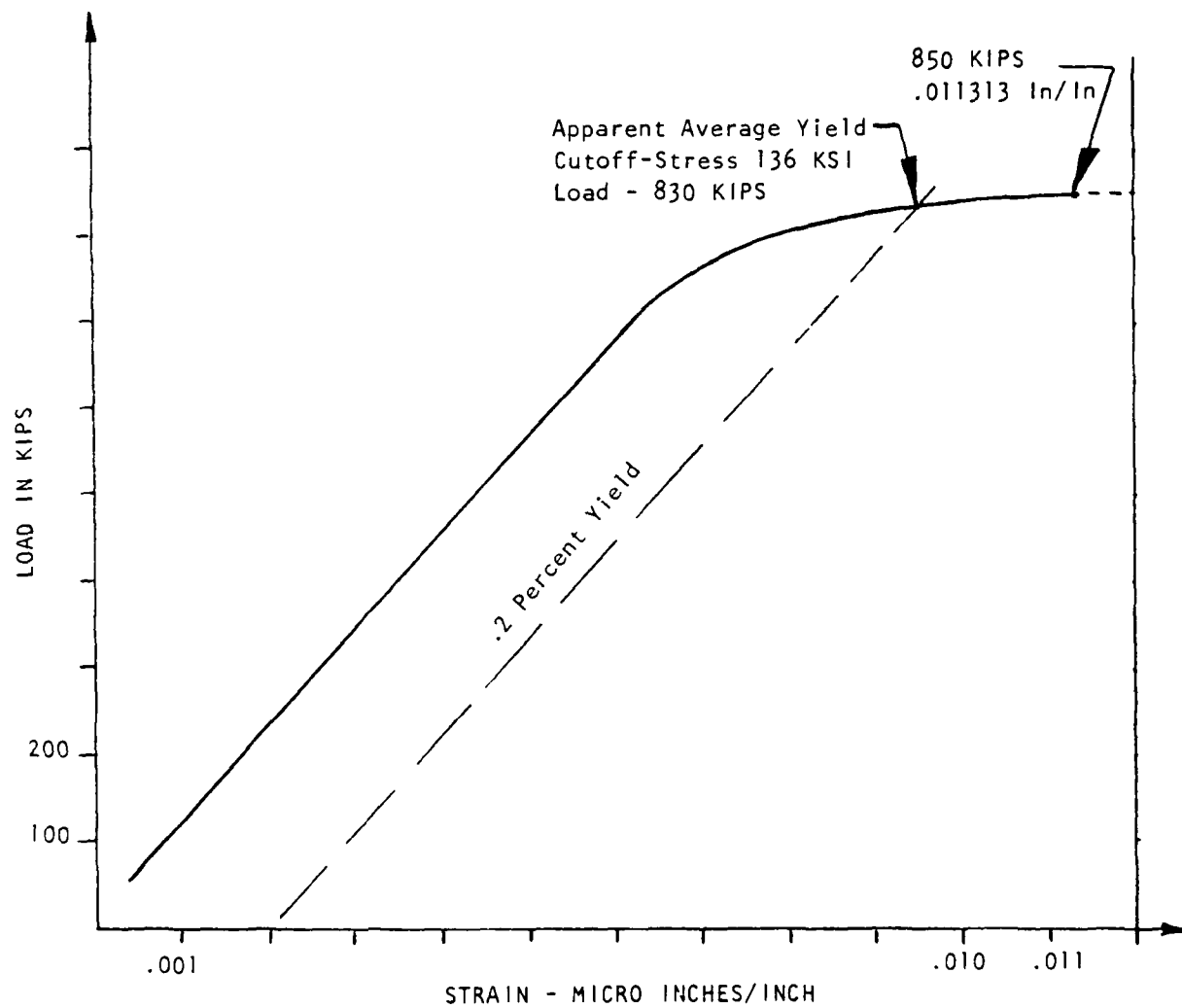


Figure 36. Load/Stress - Strain Plot of the Eighth Axial Strain Gage Average Readings.

The final failure of the cylinder at 948 KIPS was 185 percent of the design load.

The test results analysis is presented in more detail in the "Landing Gear Truss Core Outer Cylinder Structural Test Analysis Report," (Appendix C).

The cylinder specimen failure was a near uniform mushrooming of the top end. The outer sleeve locally buckled outwardly and cracked radially, while the inner sleeve buckled outwardly in the same area as the outer sleeve, cracking radially and partially splitting longitudinally in the buckled area at the corner of the truss node bands in several places. The longest split was approximately 2.4 inches from the end. All the truss members appear to have buckled equally in their total length of six inches. See figures 37 and 38.



Figure 37. Cylinder Test Specimen Inner Sleeve Longitudinal Split.

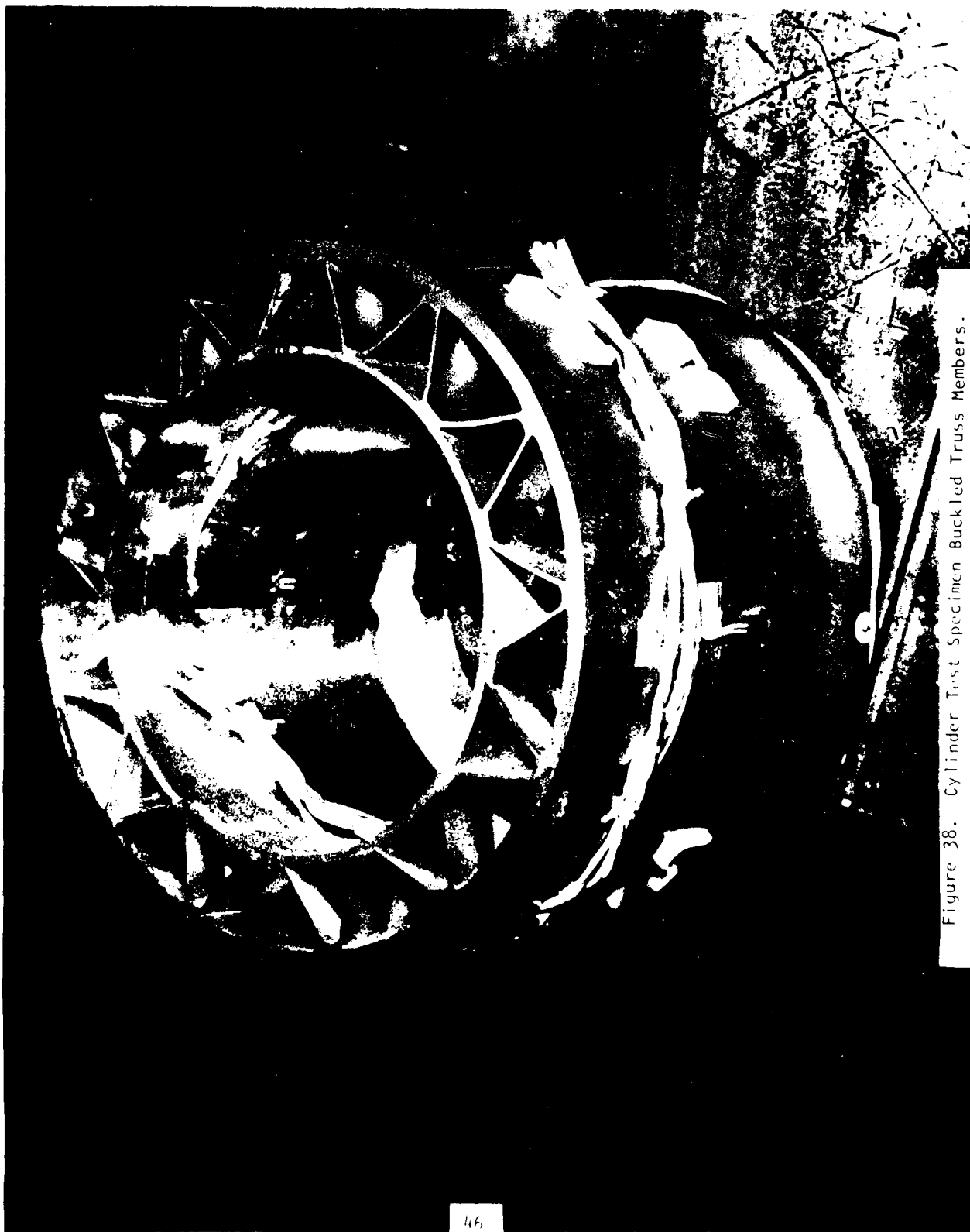


Figure 38. Cylinder Test Specimen Buckled Truss Members.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

This program demonstrated that a titanium truss core cylinder can be fabricated using SPF/DB technology. Five producibility development specimens were required to perfect the process before the test specimen was fabricated. Each producibility specimen solved problems peculiar to cylindrical truss core sandwich. The joints of the sleeve halves were a problem until a bevel lap joint was developed. It was discovered that a butt joint does not adequately bond, even when sandwiched between a node and a sleeve. When this joint was modified into a bevel lap joint, it successfully bonded.

Significant developments were made in the application of stop-off. One was using a maskant material applied to the cleaned surfaces of the core for the pattern in lieu of rolling the stop-off compound through a stencil. After spraying the stop-off compound over the entire surfaces, the maskant pattern was peeled off, exposing the bare metal surfaces to be bonded. This application not only solved the problem of applying a pattern of stop-off to pre-formed parts, but a sharper and more precise edge is obtained where the stop-off ends and the bare metal is exposed.

In addition, several improvements to the process, which will be incorporated into future panels, were identified. These include improvements to the forming dies wherein larger interlocking die halves will be used to resist opening up at the parting line under heat and pressure from the tapered plugs.

Another improvement is that by chemical milling the stop-off area below the surface of the bare metal area it is possible to use only three sleeves instead of five. The stop-off compound being below the surface would not be smudged or scraped off when the inner and outer sleeves are slid on.

The structural analysis and subsequent structural test has proved that this design is capable of meeting the landing gear loads that a cylinder of this type would be subjected to in most current, first-line fighter aircraft.

The weight and cost comparisons show a weight savings of 8.45 percent and a 33 percent reduction in life cycle costs.

2. RECOMMENDATIONS

This program has established a base for applying SPF/DB titanium truss core sandwich technology to the fabrication of cylindrical truss core structure. For this program a section of a landing gear outer cylinder was fabricated. The fabrication process is, of course, applicable to any tubular shaped structural members. In order to reap maximum benefits from the knowledge gained in expanding the state-of-the-art of the SPF/DB titanium fabrication process, further development work should continue so that the momentum of progress is not lost. This development effort should include fabrication of larger, longer and more complex tubular structural members, including full sized landing gear cylinders and other structural parts.

It is felt that the immediate need is for additional cylinders, designed for this program, which should be fabricated and tested to establish a broader data base. A logical next step is to fabricate longer cylinders to solve any problems associated with scale-up prior to fabrication of a full sized landing gear cylinder. These longer cylinders should be subjected to more complete, combined loads testing to further expand the data base.

After completion of this long cylinder program, the SPF/DB technology should be extended by the design, fabrication and testing of a complete landing gear outer cylinder, including all bosses, lugs and fittings associated with the mechanical requirements for landing gear operation. The testing of the SPF/DB outer cylinder should be followed by complete system testing in the Air Force Landing Gear Test Laboratories at AFWAL.

Following completion of successful system testing in the laboratory, a complete landing gear system should be flight tested to supply the confidence necessary for the application of the SPF/DB landing gear to a production contract.

This cylindrical sandwich technology is applicable to many other structural members and should have broad application to a wide variety of circular airframe structural components. A partial list of possible structural applications would include:

- Landing gear braces
- Large beam truss members
- Torque shafts
- Cylindrical fuel tanks, external and internal
- Rotary missile launcher
- Missile structure

The application of the SPF/DB titanium technology, demonstrated in this program, should be expanded by the design, fabrication and test of a number of the structural members listed.

APPENDIX A

LANDING GEAR TRUSS CORE OUTER CYLINDER STRESS ANALYSIS AND WEIGHT STUDY

STRESS ANALYSIS AND WEIGHT STUDY

The loads were taken from NA-62-190 App. VI Page 2-2-23 which is the F-100 F-20 Main Gear Outer Cylinder Analysis, figure A-1. The material used was AMS 6427, H. T. 220 ksi. The critical section was taken as Section D-D with an I. D. of 4.750 in. The loads on the cylinder at this section are tabulated in figure A-2, table 1.

The SPF/DB titanium cylinder has an I.D. of 4.750 in. and several trials were made varying the inner shell thickness, the outer shell thickness, the basic core thickness (T_N), the core height, and the number of nodes. It was found that the total area varies from 6.32 in.² to 6.75 in.², or 6.4 percent. This change in area times the density (.160 lb/in.³) amounts to .069 lb/in. weight difference.

A configuration of:

$$\begin{aligned} 13 \text{ nodes} & \quad (B = 27.692^\circ) \\ T_i & = .090 \text{ Inner Shell} \\ T_N & = .080 \text{ Core Thickness, BASIC} \\ T_o & = .186 \text{ Outer Shell} \\ C & = .750 \text{ Core Height} \\ b_N & = .25 \text{ Node Width} \end{aligned}$$

gives a total area of 6.4928 in.² with a margin of safety = + .002 in. combined compression and shear and no buckling occurs.

$$\text{Weight of Ti Cylinder} = 6.4928 \times .160 = 1.0388 \text{ lb/in.}$$

$$\text{Weight of Steel Cylinder} = \frac{\pi}{4} (5.260^2 - 4.750^2) \times .283 = 1.1347 \text{ lb/in.}$$

Weight Savings of 8.45 percent

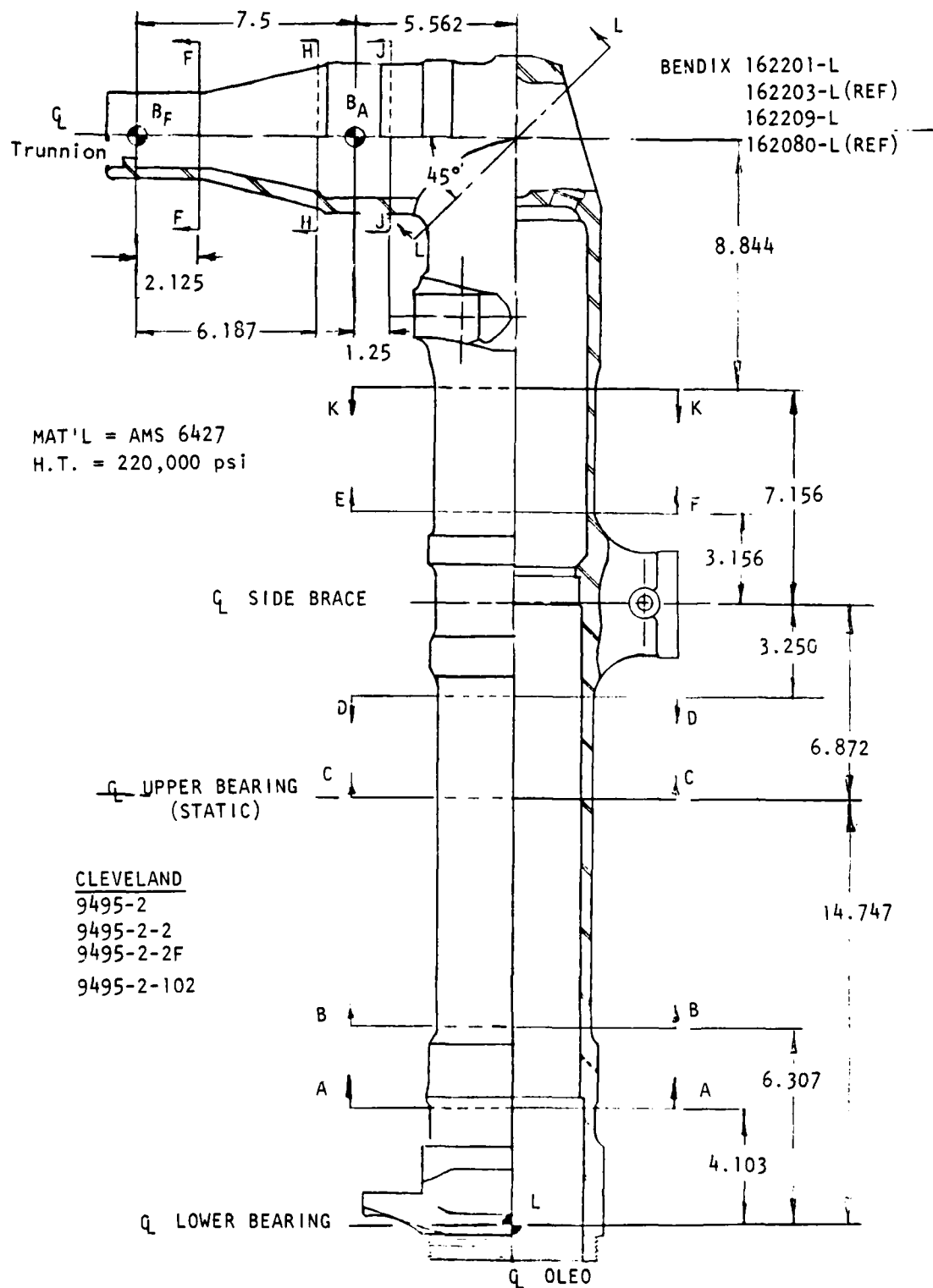





Figure A-1. Main Gear Outer Cylinder & Trunnion

Ref. Pages 2-1-22, 2-1-25, 2-1-17, 2-1-18, 2-1-20
App VI.

Section	Cond.	V 	D	S	D 	M _V	M _D	M _S	M _D 	M _S
A-A	7000a	0	51967	59599	79073	240419	-110707	213221	240248	
A-A	7002c	0	-64858	-2111	64892	-263298	-140708	-269793	304281	
B-B	7000a	0	51967	59599	79073	241850	-242063	327756	407454	
B-B	7002c	0	-64858	-2111	64892	-264326	-136056	-414717	436465	
C-C	7005b	0	55914	43986	71142	211122	-572819	824564	1004006	
C-C	7000a	0	26132	8239	27400	245911	-617667	704046	936586	
D-D	7005b	0	21570	6801	22617	212167	-600008	905885	1086571	
D-D	7000a	0	26132	8239	27400	247618	-651505	803113	1034142	
E-E	7002c	-42451	-29167	-6734	29934	-286017	-19248	-1160411	1160571	
E-E	7005b	-3819	21570	-36715	42582	496392	-467549	866300	984417	
K-K	7002c	-42451	-29167	-6734	29934	286869	7446	-1279122	1279144	
K-K	7000a	-10825	26132	-40077	47844	564968	-352602	880825	948791	
K-K	7005b	-3819	21570	-36715	42582	496624	-324709	958572	1012075	


* Includes Actuating Cylinder Reactions (All loads include secondary effects and are normal and parallel to the trunnion axis.)
 Indicates Tension

Figure A-2, Table 1. Main Gear Outer Cylinder Ultimate Section Loads

SPF/DB LANDING GEAR

CYLINDER

Cond. 7005b Sect. D-D

Material: Ti 6Al-4V SPF/DB

Vert. P_v 0 LB
 Side P_s 22617 LB
 Torque T 212167 IN-LB
 Moment M 1086571 IN-LB

F_{tu} 125000 psi
 F_{su} 76000 psi
 F_{cy} 117000 psi
 E 16.4×10^6 psi
 μ .33

$f_{bx} = MC_x/I$ Outer Middle Inner
 f_b 115500 99100 84430

$$\text{Core } \frac{\sigma_{cr}}{\eta} = K \frac{T^2 E}{12(1-\mu^2)} \left(\frac{1}{b/t} \right)_m^2 \quad K = 4 \text{ Simple Supt.}$$

$$= 4 \times 15.13686 \times 10^6 / (18.033)^2 = \underline{186190} \text{ psi}$$

$$\sigma_{cr} = \underline{115200} \text{ psi} \quad \text{Ref. Curve C} \quad R_{bend} = \underline{.860}$$

Skins Curved Panel	t/R	$\frac{\sigma_{cr}}{\eta}$	σ_{cr}	R_{bend}
$\frac{\sigma_{cr}}{\eta} = .3E \frac{t_x}{R_x}$ Outer	<u>.05623</u>	<u>276650</u>	<u>117000</u>	<u>.987</u>
Inner	<u>.03719</u>	<u>182970</u>	<u>115100</u>	<u>.734</u>

$$A_{SHR} = \frac{13}{(A_o + A_i)} = \underline{5.2351} \text{ in}^2$$

$$f_s = \frac{2P_s}{A_{SHR}} = \underline{8641} \text{ psi} \quad R_s = \underline{.114}$$

$$J/r = 2I_{CYL}/R_x$$

	J/r	f_{st}	R_{st}
$f_{st} = T/(J/r)_x$ Outer	<u>18.822</u>	<u>11272</u>	<u>.148</u>
Inner	<u>25.729</u>	<u>8246</u>	<u>.109</u>

$$\text{Assume } F_{st} = F_{su}$$

$$\text{Outer MS} = \frac{1}{R_{bend} + R_s} - 1 = \underline{+.002}$$

SPF/DB LANDING GEAR

CYLINDER

$$\begin{aligned}\beta &= 27.692^\circ \\ N &= 13 \text{ No. of Segments} \\ t_i &= .09 \text{ in} \\ t_o &= .186 \text{ in} \\ t_n &= .08 \text{ in} \\ C &= .75 \text{ in} \\ b_N &= .25 \text{ in} \\ R_{id} &= 2.375 \text{ in} \\ \bar{t} &= t_i + t_o + t_n = .356 \text{ in}\end{aligned}$$

$$\begin{aligned}R_a &= R_{id} + t_i = 2.465 \text{ in} \\ R_m &= R_a + C/2 = 2.840 \text{ in} \\ R_b &= R_a + C = 3.215 \text{ in} \\ R_{od} &= R_b + t_o = 3.401 \text{ in}\end{aligned}$$

$$\begin{aligned}R_i &= R_{id} + t_i/2 = 2.420 \text{ in} \\ R_o &= R_{od} - t_o/2 = 3.308 \text{ in} \\ R_{nc} &= R_a + t_n/2 = 2.505 \text{ in}\end{aligned}$$

$$\begin{aligned}h_c &= C - t_n = .670 \text{ in} \\ S_x &= R_x^3 \text{ RAD}; S_o = 1.5988 \text{ in} \\ S_m &= 1.3726 \text{ in} \\ S_i &= 1.1696 \text{ in} \\ S_{NC} &= 1.2107 \text{ in}\end{aligned}$$

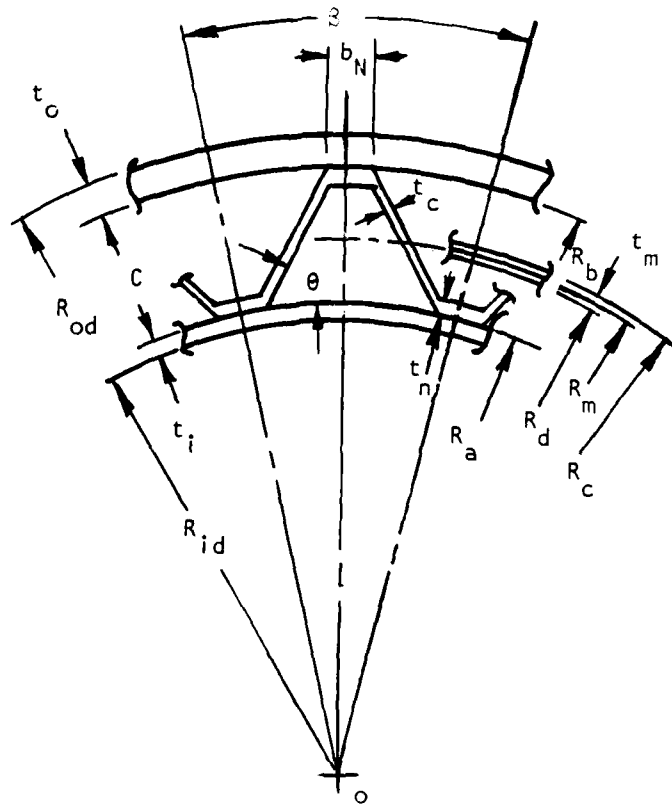
$$L_i = 2R_i \sin \frac{\beta}{2} = 1.1588 \text{ in}$$

$$\tan \theta = 2h_c / (L_i - b_N) = 1.4253$$

$$\theta = 55.8699^\circ$$

$$b_c = h_c / \sin \theta = .8094 \text{ in}$$

$$t_c = t_n \cos \theta = .0449 \text{ in}$$



$$\begin{aligned}A_N &= b_n t_n = .0200 \text{ in}^2 \\ A_C &= b_c t_c = .0363 \text{ in}^2 \\ A_{NC} &= S_{NC} t_N = .0969 \text{ in}^2\end{aligned}$$

$$A_i = S_i t_i = .1053 \text{ in}$$

$$A_o = S_o t_o = .2974 \text{ in}$$

$$A_{seg} = A_{NC} + A_i + A_o = .4996 \text{ in}^2$$

$$\begin{aligned}I_{CORE} &= A_N \left(R_a + \frac{t_N}{2} \right)^2 + A_N \left(R_b - \frac{t_N}{2} \right)^2 \\ &\quad + 2A_C (R_m)^2 + A_C \frac{(h_c)^2}{b} \\ &= .9159 \text{ in}^4\end{aligned}$$

$$t_m = I_{CORE} / (R_m)^2 S_m = .0827 \text{ in.}$$

SPF/DB LANDING GEAR

CYLINDER

$$R_c = R_m + t_m/2 = \underline{2.8814} \text{ in}$$

$$R_d = R_m - t_m/2 = \underline{2.7986} \text{ in}$$

$$I_{CYL} = \frac{\pi}{4} (R_{od}^4 - R_b^4 + R_c^4 - R_d^4 + R_a^4 - R_{id}^4) = \underline{31.1323} \text{ in}^4$$

$$C_o/I_{CYL} = R_o/I_{CYL} = \underline{.1063} \text{ in}^{-3}$$

$$C_m/I_{CYL} = R_m/I_{CYL} = \underline{.0912} \text{ in}^{-3}$$

$$C_i/I_{CYL} = R_i/I_{CYL} = \underline{.0777} \text{ in}^{-3}$$

$$b_i = S_i - b_n = \underline{.9196} \text{ in}$$

$$b_o = S_o - b_n = \underline{1.3488} \text{ in}$$

$$b_o/t_o = \underline{7.2517}$$

$$b_i/t_i = \underline{10.2181}$$

$$b_c/t_c = \underline{18.0326}$$

$$t_o/R_o = \underline{.4987}$$

$$t_i/R_i = \underline{.2413}$$

$$A_{TOTAL} = (\text{No. of Segments}) \times A_{SEG} = \underline{6.4948} \text{ in}^2$$

APPENDIX B

LANDING GEAR TRUSS CORE OUTER CYLINDER STRUCTURAL TEST PLAN

1.0 INTRODUCTION

A main landing gear outer cylinder part made from titanium and using the superplastic formed/diffusion bonded (SPF/DB) process is to be tested.

2.0 OBJECTIVE

To verify that the strength and stability requirements for the F-100 main landing gear outer cylinder are met by the SPF/DB titanium design.

The testing will be done on the basis that the worst-case or critical load condition on the outer cylinder from a strength and stability standpoint is expected to be the axial compression stresses due to bending loads. The three best specimens are to be tested to failure in static axial compression at room temperature.

Since the compression stress due to the bending load is the critical condition, the ability of the truss core cylinder to withstand this stress can be determined using a straight axial compression test rather than a more expensive bending test.

3.0 SPECIMEN DESCRIPTION

The specimens will be a 6-inch section of the outer cylinder, which is titanium in a truss core sandwich configuration made using the SPF/DB fabrication method. The cylinder ends will be ground flat, normal to the cylinder axis and parallel within 0.005-inch per foot to insure uniform load introduction.

Tests will be conducted on the best three specimens which have been NDI inspected and found satisfactory.

4.0 TEST SET-UP

All tests will be conducted using existing equipment currently available at the NAAD Structures Test Laboratory. A schematic of the test setup is shown in figure B-1.

5.0 INSTRUMENTATION

A total of eight axial strain gages will be installed back-to-back on each specimen, with four on the inner face sheet surface and four on the outer face sheet on the midlength centerline at the 90° location around the cylinder perimeter and deflection transducer gages will be used to measure radial deflection of the cylinder wall at points in line with the strain gages and midway between them around the perimeter, figures B-1 and B-2.

6.0 PROCEDURE

The loads will be applied in 10 percent increments of predicted ultimate load so that instrumentation readings may be made and recorded. Curves of test machine load versus head deflection will also be recorded. Continuous loading in 10 percent increments will be made to failure, with reading and recording at each increment.

7.0 RESULTS

A complete test report will be made, and the results will be included in the final report.

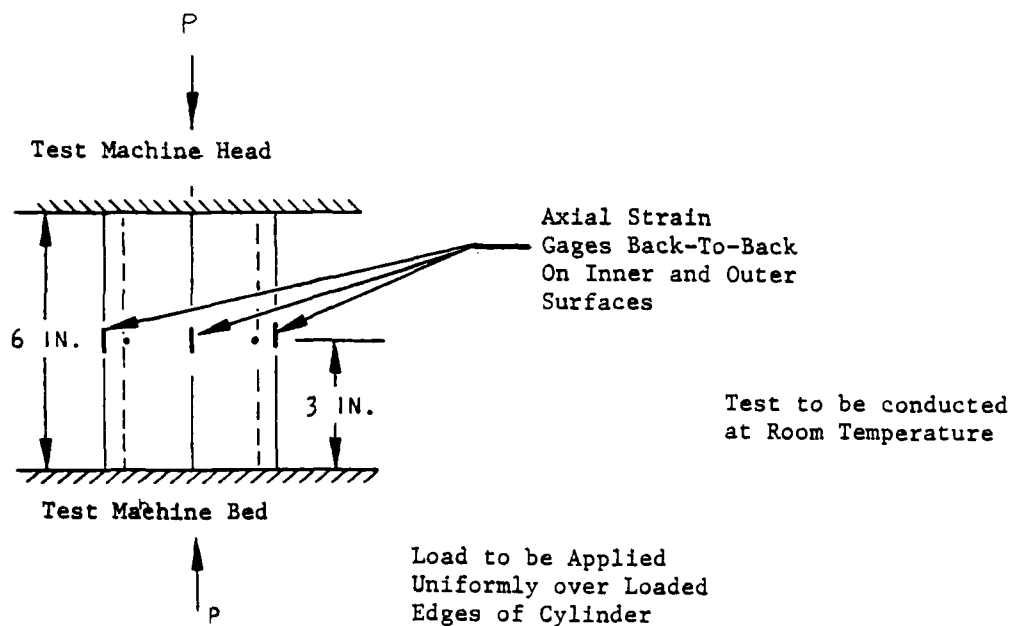


Figure B-1. SPF/DB Ti MLG Outer Cylinder Segment Test - Side View

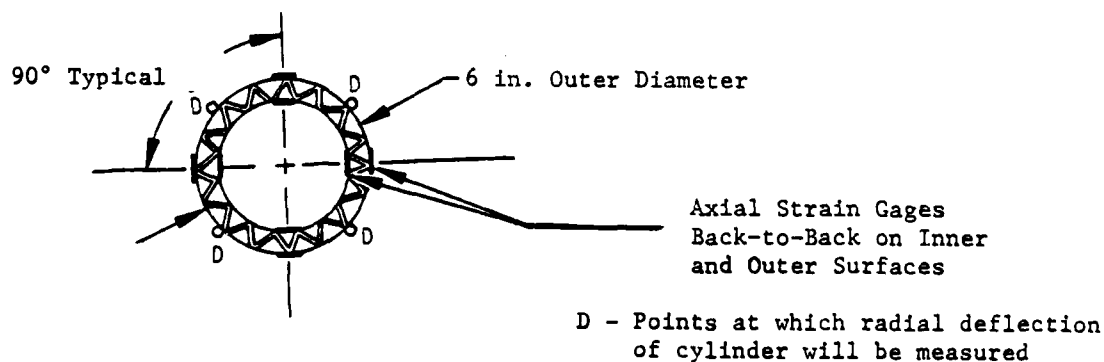


Figure B-2. SPF/DB Ti MLG Outer Cylinder Segment Test - End View

APPENDIX C

LANDING GEAR TRUSS CORE OUTER CYLINDER STRUCTURAL TEST ANALYSIS REPORT

1.0 INTRODUCTION

A main landing gear outer cylinder part made from titanium and using the superplastic formed/diffusion bonded (SPF/DB) process was successfully tested to 158 percent of design load. Evaluation of the data in terms of nonlinear behavior indicates that yield (.2 percent offset) occurred at the expected 135 to 139 Ksi test yield value range.

2.0 OBJECTIVE

To verify that the strength and stability requirements for the F-100 main landing gear outer cylinder are met by the SPF/DB titanium design.

The testing was done on the basis that the worst-case or critical load condition on the outer cylinder, from a strength and stability standpoint, is expected to be the axial compression stresses due to bending loads. The cylindrical specimen was tested to failure in static axial compression at room temperature.

Since the compression stress due to the bending load is the critical condition, the ability of the truss core cylinder to withstand this stress was determined using a straight axial compression test rather than a more expensive bending test.

3.0 SPECIMEN DESCRIPTION

The specimen was a 6-inch section of the outer cylinder, which is titanium in a truss core sandwich configuration made using the SPF/DB fabrication method. The cylinder ends were ground flat, normal to the cylinder axis and parallel within 0.005-inch per foot to insure uniform load introduction. The pertinent sandwich face and core thickness dimensions are provided in Section III (figure 34) of the main report. The cross-sectioned area was calculated to be 6.098 square inches based on weighted average thicknesses.

4.0 TEST SET-UP

The test was conducted using a 1500 K test machine at the NAAD Structures Test Laboratory. A schematic of the test setup is shown in figure C-1. A photograph of the test setup is provided in figure 35. the main report.

5.0 INSTRUMENTATION

A total of eight axial strain gages were installed back-to-back on the specimen, with four on the inner face sheet surface and four on the outer face sheet on the mid-length centerline at the 90° location around the cylinder perimeter, and four deflection transducer gages were used to measure radial deflection of the cylinder wall at points in line with the strain

gages and midway between them around the perimeter, figures C-1 and C-2.

6.0 PROCEDURE

The load was applied in 100 kip increments up to 200 kip load. Thereafter the load was applied in 50 kip load increments to failure. This deviates from the test plan that stated the load would be applied in 10 percent increments. Deflection and strain gage readings were measured and recorded at each increment of load level.

7.0 RESULTS

7.1 STRAIN GAGE - DEFLECTION DATA

Axial strain gage readings and radial deflection values are shown in figures C-3 and C-4 respectively. Figure C-5 summarizes the average strain versus test load or stress in graphical form to demonstrate that the test specimen attained its ultimate capability, in that stresses exceeded the conventional 0.2 percent offset yield stress. Based on figure C-5 an average compressive yield stress of 136 ksi was attained. Figure C-6 presents a typical back-to-back strain gage versus load/stress plot which shows no buckling instability behavior. The test compressive yield strength of 139 ksi agrees well with the average data of 136 ksi. The 136 - 139 ksi yield strengths correlate very well with expected basic compression coupon test data (135 ksi) from prior programs. Load versus radial deflection data are plotted in figure C-7 and show that there was no general or local instability failures evident below 750 kips. Strain gage data in figures C-5 and C-6 also indicate linear behavior up to about 750 kips.

7.2 TEST VERSUS PREDICTED CORRELATION

Ultimate failure load occurred at 948 kips or a calculated stress of 155 ksi. Due to the excessive lateral deformation, figure C-7 and axial strain, figure C-5, at this load level it should be emphasized that this is not the load to use for structural design. The conventional structural design limits the useable stress level to compressive yield strength as the upper limit and uses a minimum guaranteed or design allowable value lower than that exhibited by actual test data. The predicted design load of 600 kips was based on a material system which had a compressive yield strength of 117 ksi. The estimated yield strength of the test specimen is 136 ksi from figure C-5. The predicted critical load (P_{cr}) is therefore assumed proportional to yield strengths and test area which yields a predicted test load of 735 kips.

The comparable test load (P_{cr}) is selected from figure C-5 and C-7, at 750 kips where the strain and deflection readings exhibit nonlinearity. Test versus predicted of $750/735 = 1.02$ shows excellent correlation.

7.3 BENDING

The test results provided the ultimate capability of the truss core sandwich cylinder under uniaxial compression load. To extend this data for bending moment behavior, the following procedure can be used. For bending in the elastic range, the maximum stress acting on a cross-section normal

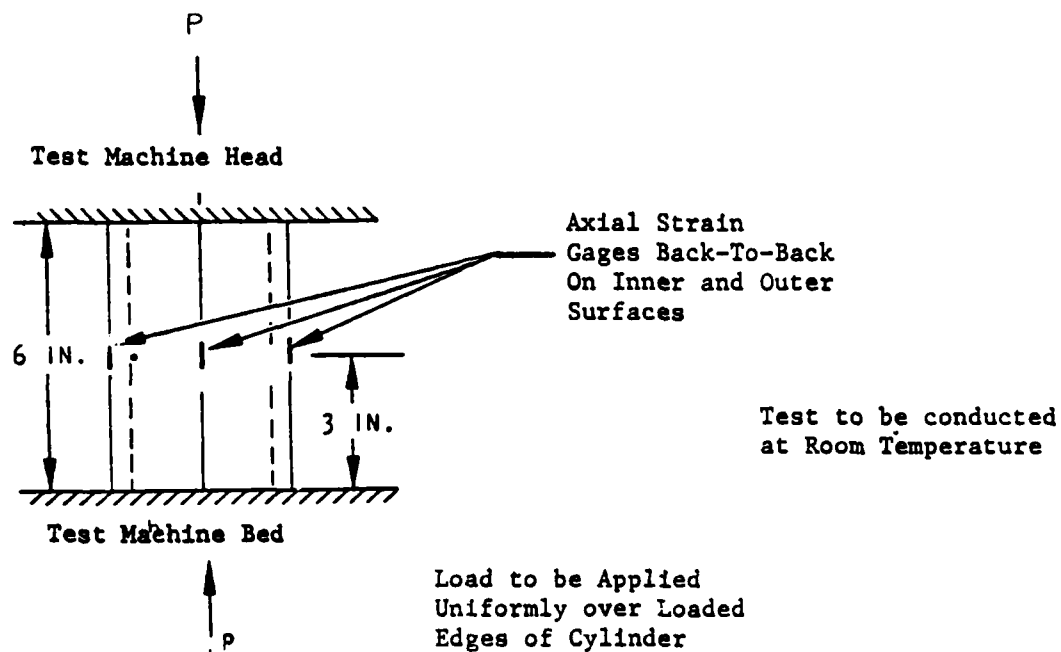


Figure C-1. SPF/DB Ti MLG Outer Cylinder Segment Test - Side View

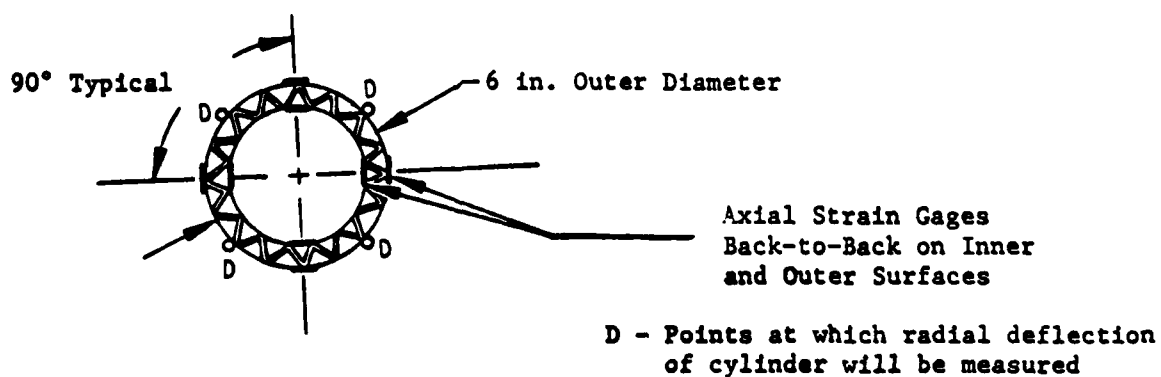


Figure C-2. SPF/DB Ti MLG Outer Cylinder Segment Test - End View

LOAD KIPS	STRAIN IN/IN (ALL READINGS ARE NEGATIVE)								STRESS PSI			
	1	2	3	4	5	6	7	8	AVERAGE	END 1	END 2	
0	0	0	0	0	0	0	0	0	-	-	-	
100	843	495	1,014	572	1,017	566	1,157	650	790	16,359	16,439	
200	1,656	1,377	1,936	1,501	1,880	1,451	2,061	1,567	1,678	32,717	32,877	
250	2,059	1,785	2,383	1,977	2,307	1,907	2,500	2,031	2,119	40,896	41,097	
300	2,471	2,241	2,832	2,457	2,734	2,368	2,939	2,499	2,568	49,076	49,316	
350	2,881	2,695	3,277	2,936	3,159	2,826	3,373	2,966	3,014	57,255	57,536	
400	3,295	3,154	3,723	3,420	3,585	3,289	3,810	3,437	3,464	65,434	65,755	
450	3,712	3,616	4,172	3,906	4,017	3,756	4,248	3,910	3,915	73,614	73,974	
500	4,129	4,078	4,620	4,394	4,443	4,222	4,687	4,384	4,370	81,793	82,194	
550	4,548	4,542	5,068	4,882	4,873	4,690	5,126	4,860	4,824	89,972	90,413	
600	4,972	5,011	5,519	5,377	5,310	5,164	5,563	5,342	5,282	98,151	98,633	
650	5,408	5,496	5,976	5,890	5,759	5,658	5,992	5,838	5,752	106,331	106,852	
700	5,864	6,009	6,433	6,435	6,219	6,190	6,408	6,369	6,241	114,510	115,071	
750	6,422	6,629	6,954	7,158	6,700	6,867	6,857	7,069	6,832	122,689	123,291	
800	7,090	7,580	7,874	8,678	7,374	8,227	7,778	8,644	7,918	130,869	131,510	
850	9,511	11,230	11,060	13,170	10,041	12,434	10,946	12,160	11,313	139,048	139,729	
900	*NR	*NR	*NR	*NR	*NR	*NR	*NR	*NR	-	147,227	147,949	
948	FAILED										155,079	155,839
Average Area = 6.098 in ²											AREA 6.113	AREA 6.083

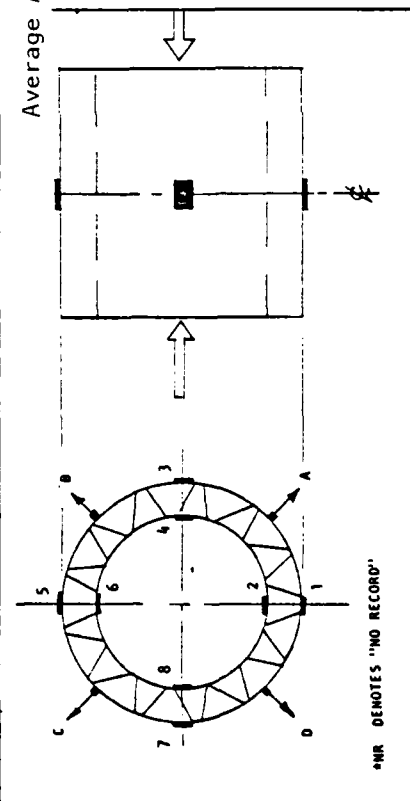


Figure C-3, Table 1 SPF/DB Cylinder Test Results - Strain Gages.

LOAD KIPS	A	B	C	D
0	0	0	0	0
100	.0118	.0088	.0029	+.0118
200	.0207	.0146	.0143	+.0266
250	.0266	.0176	.0201	.0295
300	.0295	.0234	.0258	.0384
350	.0354	.0293	.0287	.0443
400	.0413	.0322	.0344	.0502
450	.0472	.0381	.0401	.0561
500	.0532	.0410	.0430	.0591
550	.0591	.0469	.0487	.0680
600	.0650	.0527	.0544	.0739
650	.0709	.0557	.0573	.0769
700	.0760	.0615	.0602	.0827
750	.0856	.0644	.0630	.0887
800	.1063	.0703	.0659	.1035
850	.1506	.0937	.0802	.1360
900	.2392	.1434	.1117	.2099
948	*NR	*NR	*NR	*NR

ALL READINGS NEGATIVE EXCEPT
AS SHOWN

*NR DENOTES "NO RECORD"

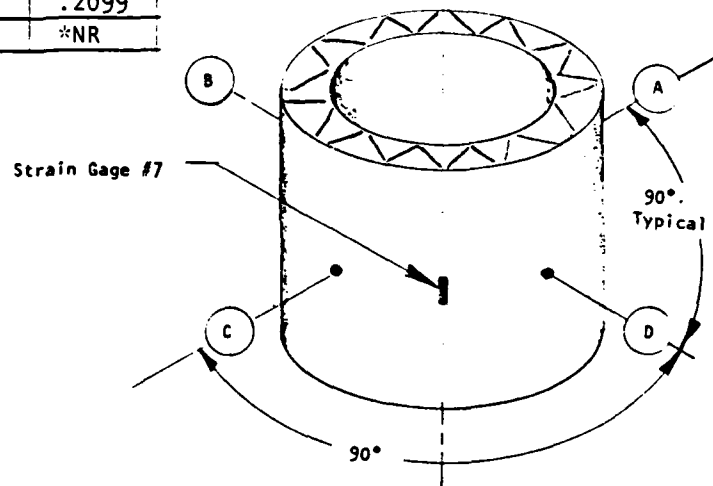


Figure C-4, Table 2. SPF/DB Cylinder Test Results -
Radial Defl. (Inch)

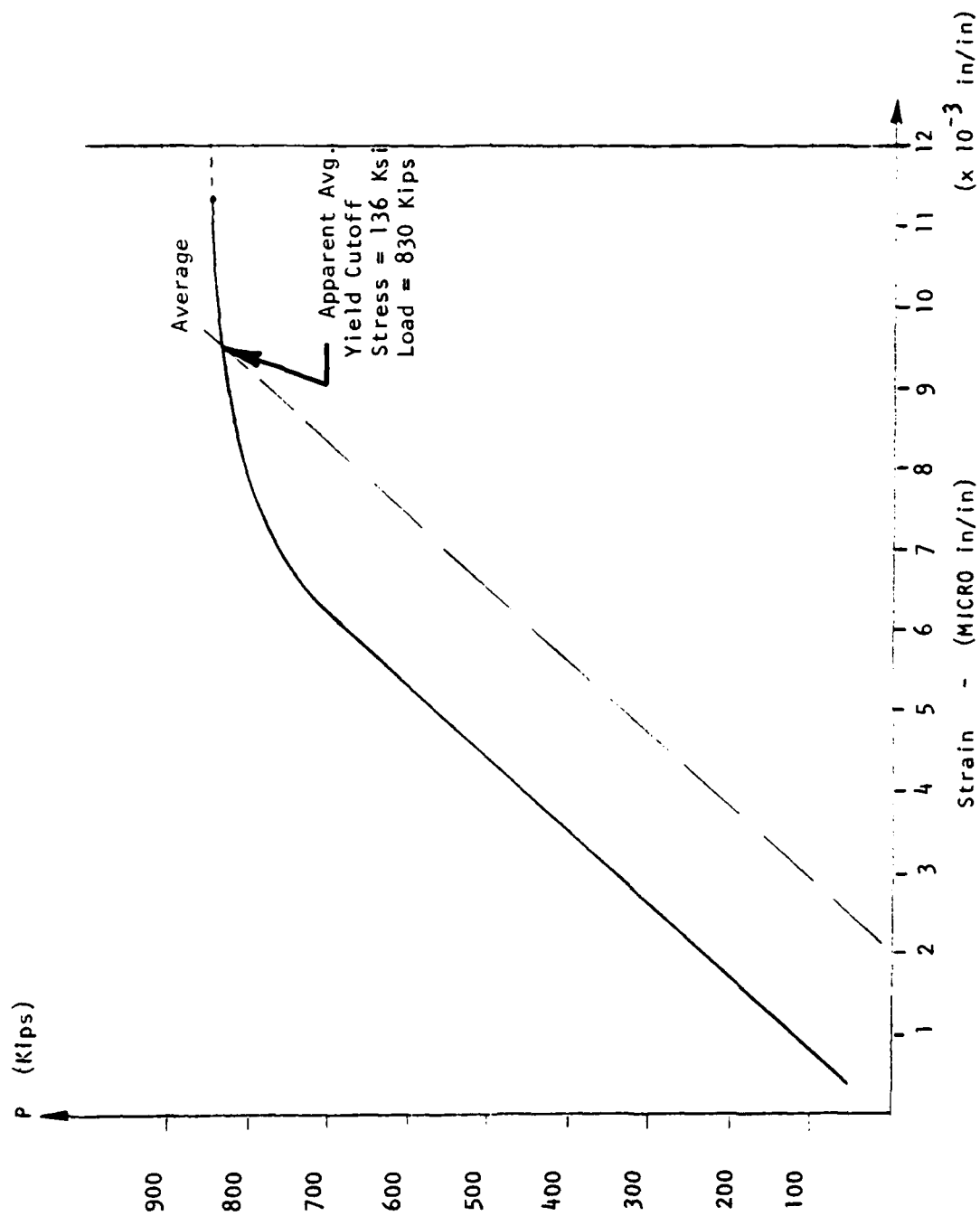


Figure C-5. Load/Stress-Strain - Average Strain Gage Data

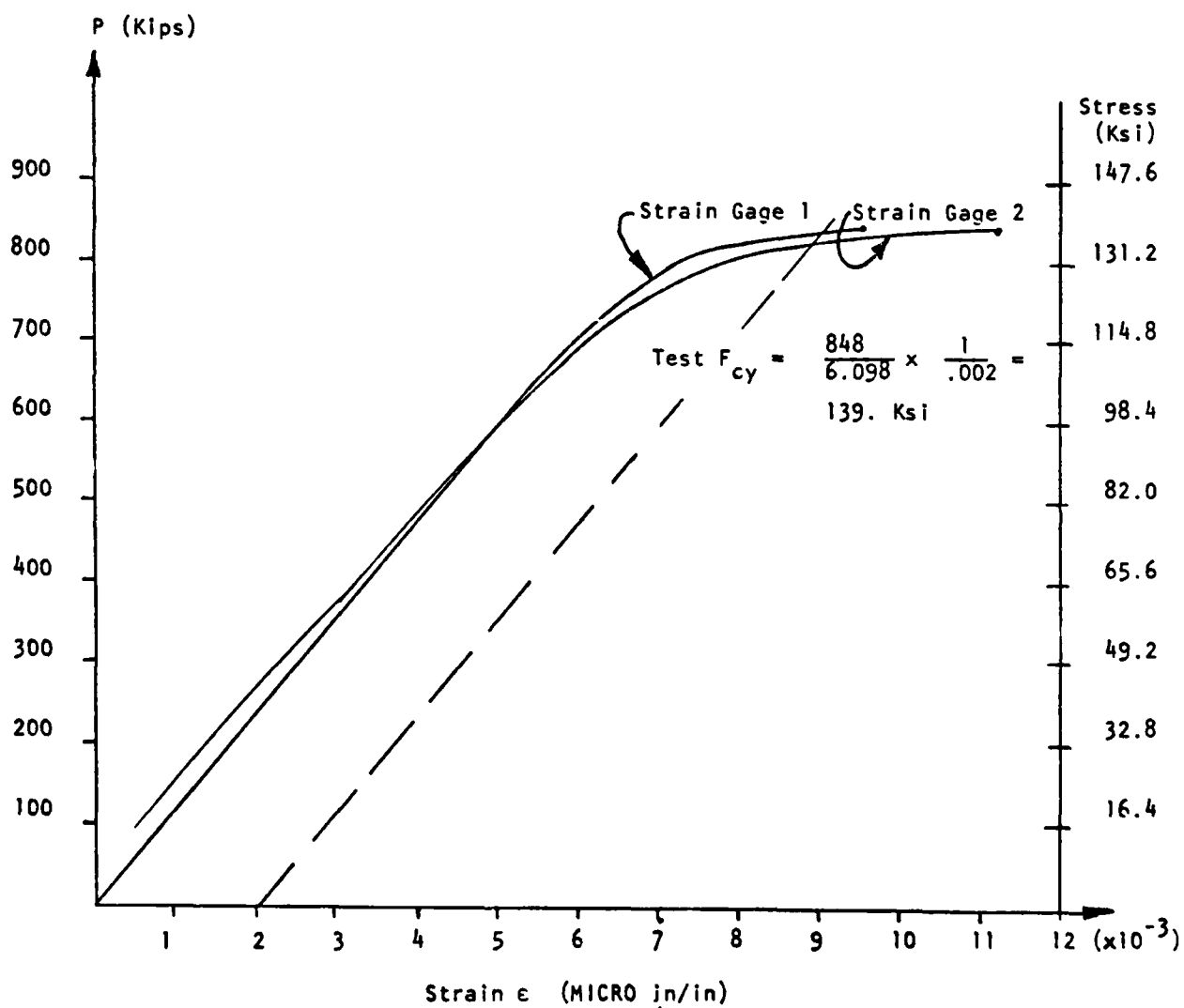
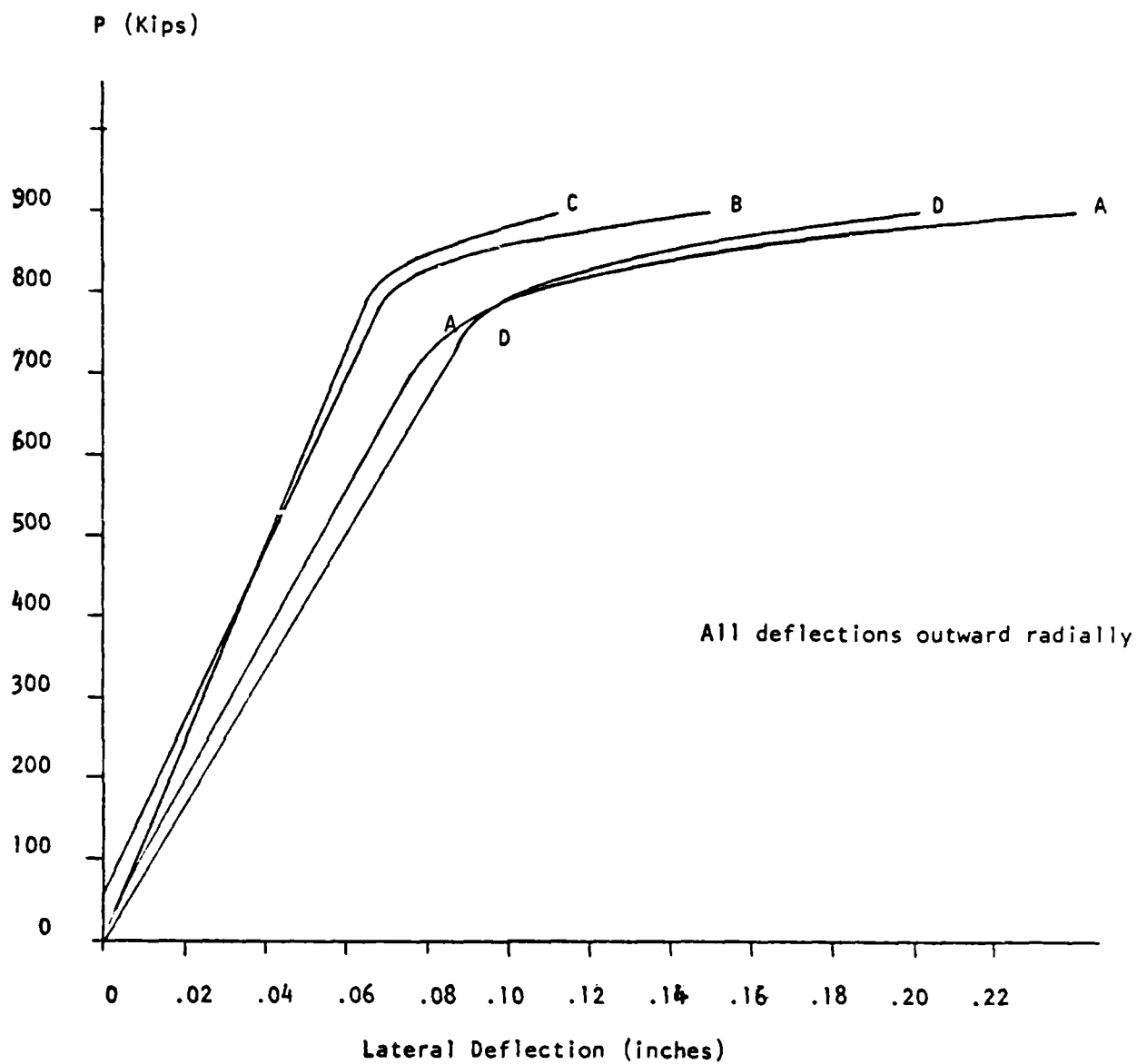


Figure C-6. Load/Stress-Strain, Gages No. 1 & 2



	P_1	P_2	$P = P_2 - P_1$	ΔL_1	ΔL_2	ΔL
A	18	700	682	0	.076	.076
B	50	700	650	0	.060	.060
C	0	700	700	0	.057	.057
D	0	700	700	0	.083	.083

Figure C-7. Test Load versus Radial Deflection

to the longitudinal axis is given by the conventional flexure formula:

$$f_b = \frac{My}{I} \quad \text{where: } M = \text{Bending Moment}$$

$$y = \text{Outer radius distance}$$

$$I = \text{Moment of inertia of cross-section}$$

For inelastic or plastic bending and to use the nonlinear portion of the stress-strain curve, the concept of "bending modulus of rupture, F_b " can be used. This "effective" (fictitious) maximum bending stress, F_b , based on trapezoidal theory is:

$$F_b = \frac{M y}{I} = f_1 + f_2 \left(\frac{2Q}{I/y} - 1 \right)$$

where: f_1 = stress at the outer face sheet

f_2 = intercept stress = stress required for a trapezoidal stress distribution to produce the same moment about the neutral axis as the actual stress distribution on the area between the neutral axis and the outer face sheet.

Q = Statical Moment

The term $\frac{2Q}{I/y}$ is defined as the section factor K and for the truss core sandwich cylinder configuration described in this section is 1.36. (For single thickness tube sections, this value ranges from 1.27 to 1.70 depending on wall thickness.) The estimated:

$$F_b = f_1 + f_2 (K - 1)$$

where: f_1 = Maximum allowable stress in extreme fiber =
 $F_{cy} = 136 \text{ ksi (test)}$

f_2 = Intercept stress = 41 ksi

$K = 1.36$

$$f_b = 136 \times 41 (.36) = 151 \text{ ksi}$$

The predicted test moment is:

$$M = [f_1 + f_2 (K-1)] \frac{I}{R_o} = F_b \frac{I}{R_o}$$

where: R_o = Radius of outer shell = $[151] 27.29/3.31 =$

1245. in-Kips

Test verification is recommended for bending behavior.

8.0 CONCLUSIONS

The significant finding is that the nonlinear behavior above 750 kips load indicates material yielding and that the outer surface of the cylinder symmetrically deformed radially outward at the four deflection monitoring locations. The final failure load of 948 kips or 158 percent of the design load of 600 kips is the ultimate capability of this test configuration. However, for uniaxial compression load it is recommended that a structure of this type be designed up to a maximum of the conventional compressive yield cutoff or less to account for material nonlinearity behavior.

However, for bending moment loads, the material nonlinearity can be used such as in the case for conventional unstiffened tubing to obtain an effective bending modulus of rupture F_b . For preliminary structural design an effective F_b equivalent to 151/136 or 1.11 F_y can be used for this specific configuration. Generally for tube sections C_y bending allowables are determined empirically and additional experimental verification is recommended.

(PREDICTED DESIGN LOAD)

Inner $t = .175$ (before machining)

Reduce to .090 Note: (After machining:

Actual Average $t = .096$ inch

Min. Meas. $t = .082$ inch)

$$\text{Dia.} = 4.500 + (2 \times .0858) = 4.6716$$

$$R = 2.3358$$

Outer $t = .1598$

$$R_{od} = 6.780/2 = 3.390$$

Assuming: $t_N = .072$ spaced equally with $N = 13$

$$\beta = 27.692^\circ = .483317 \text{ RAD.}$$

$$t_i = .090$$

$$t_o = .1598$$

$$t_N = .072 \quad b_N = .25$$

$$C = 1.140 - .0858 - .090 - .1598 = .8044$$

$$R_{id} = 2.3358$$

$$\bar{t} = .3218$$

$$R_a = 2.3358 + .090 = 2.4258$$

$$R_M = 2.4258 + .4022 = 2.8280$$

$$R_b = 2.4258 + .8044 = 3.2302$$

$$R_{OD} = 3.2302 + .1598 = 3.390$$

$$R_{nc} = 2.4258 + .0360 = 2.4618$$

$$h_c = .8044 - .072 = .7324$$

$$S_x = R_x \beta \text{ RAD} \quad S_o = 1.5998$$

$$S_M = 1.3668$$

$$S_i = 1.1507$$

$$S_{nc} = 1.1898$$

$$R_i = 2.3350 + .0450 = 2.3808$$

$$R_o = 3.3900 - .0799 = 3.3101$$

$$L_i = 2 R_i \sin \frac{\theta}{2} = 2 \times 2.3808 \times .239313 = 1.1395$$

$$\tan \theta = 2 \times .7324 / 1.1395 - .25 = 1.64677 \quad \theta = 58.73^\circ$$

$$b_c = .7324 / \sin \theta = .8569$$

$$t_c = .072 \times \cos \theta = .0374$$

$$A_N = .25 \times .072 = .0180$$

$$A_c = .8569 \times .0374 = .0320$$

$$A_{NC} = 1.1898 \times .072 = .0857$$

$$A_i = 1.1507 \times .090 = .1036$$

$$A_o = 1.5998 \times .1598 = .2556$$

$$A_{SEG} = .0857 + .0136 + .2556 = .4449 \text{ in}^2$$

$$A_{TOTAL} = 13 \times .4449 = 5.7837 \text{ in}^2$$

$$I_{CORE} = .0180 (2.4258 + .036)^2 + .0180 (3.2302 - .036)^2 \\ + 2 \times .0320 (2.8280)^2 + .032 (.7324)^2 / 6 = .80745 \text{ in}^4$$

$$t_M = I_{CORE} / R_M^2 S_M = .80745 / 2.8280^2 \times 1.3668 = .0739$$

$$R_c = 2.8200 + .0370 = 2.8650$$

$$R_d = 2.8280 - .0370 = 2.7910$$

$$I_{CYL} = \frac{\pi}{4} (3.3900^4 - 3.2302^4 + 2.8650^4 - 2.7910^4 + 2.4258^4 - 2.3358^4) \\ = 27.29400 \text{ in}^4$$

$$C_{o/I_{CYL}} = .12128 \quad C_{m/I_{CR}} = .10361 \quad C_{i/I_{CYL}} = .08723$$

$$b_i = .9007$$

$$b_o = 1.3498$$

$$b_o / t_o = 8.447$$

$$b_i / t_i = 10.008$$

$$b_c / t_c = 22.912$$

$$t_o/R_o = .0483$$

$$t_i/R_i = .0378$$

Allow Load (Local Instability)

$$\text{Core } A = .0857 \text{ in}^2/\text{SEQ}$$

$$\frac{\sigma_{cr}}{\eta} = K \frac{\pi^2 E}{12(1-\mu^2)} \left(\frac{1}{b/t} \right)_m^2 = 4 \times 15.1368 \times 10^6 \left(\frac{1}{22.912} \right)^2$$

$$= 115300 \text{ psi}$$

$$\sigma_{cr} = 105200 \text{ psi}$$

$$P_{cr} = 105200 \times .0857 \times 13 = 117203 \text{ LBS}$$

SKINS - Curved Panel (Assume Core - Stabilizes faces)

$$\frac{\sigma_{cr}}{\eta} = .3E t_x/R_x$$

	$\frac{t}{R}$	$\frac{\sigma_{cr}}{\eta}$	σ_{cr}	A/SEQ	P_{cr}
Outer	.0483	237600	110200	.2556	336172
Inner	.0378	186000	108100	.1036	145589

$$* \text{ Total } P_{cr} = 598964 \text{ LBS} = 600 \text{ KIPS (Design)}$$

$$F_{cr} = 600/5.783 = 103.7 \text{ KSI}$$

$$** \text{ Let revised } P_{cr} = \frac{F_{cy}(\text{Test})}{F_{cy}(\text{Design})} \times F_{cr} \times A_{\text{Test}}$$

$$(A_{\text{test}} = 6.098 \text{ in}^2) = \frac{136.}{117.} \times 103.7 \times 6.098 = 735 \text{ KIPS Predicted}$$

$$* \text{ Based on material with } F_{cy} = 117 \text{ KSI}$$

$$** \text{ Adjusted for material with } F_{cy} = 136 \text{ KSI}$$

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